7.12 SENSITIVITY OF GROUND BASED RADIOMETRIC OBSERVATION TO ATMOSPHERIC TEMPERATURE INVERSIONS

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1. OBJECTIVE

To construct a physically based method for the retrieval of temperature inversion parameters from ground-based microwave radiometer measurements.

2. INTRODUCTION

The temperature profile of the atmosphere can be obtained by direct in-situ radiosonde measurements as well as by passive radiometer observations. Due to logistic problems, it is not possible to obtain radiosonde measurements at all places and times. Since the radiosonde measures the temperature directly, it is quite accurate. Ground-based radiometer observations around 60 GHz oxygen absorption lines are used for temperature profile estimation. The temperature estimation technique is based on a forward radiation model of various radiosonde profiles and a neural network inversion method. A thorough review of various statistical methods to retrieve the atmospheric variables using ground-based measurements can be found in Westwater (1993).

2.1 Temperature inversion

Temperature usually decreases with height in the atmosphere with a lapse rate of 6^o *K /km*. But on a number of occasions, observations show that temperature increases with height in a thin layer of atmosphere. Such a phenomenon is referred to as ``temperature inversion''. Inversions near the ground are usual during winter and night time conditions. Low level inversions can act as a `lid' which traps pollution-laden air beneath it. The study of inversions is important because natural and man-made aerosols cause poor visibility below the inversion layer while above the inversion layer, the visibility is good.

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Temperature and vapor profiles in the boundary layer determine the extent of the cloud profile and its microstructure. Temperature inversions and moisture layer parameters might be particularly useful for estimating cloud formation and its growth.

2.2 Advantage of a ground-based radiometer for the inference of temperature inversion

Emission from a layer is attenuated by the optical depth of the intervening atmosphere between the layer and instrument. Hence emission measured by a satellite-based instrument is constrained by the top of the atmosphere whereas for a ground-based radiometer, emission from lower layers dominates. So temperature inversion which occurs near the ground can be better inferred by a ground-based radiometer. Additionally, retrievals from ground-based radiometers are used as validation for satellite sensors.

3. BACKGROUND ON TEMPERATURE RETRIEVAL

The Radiometrics TP/WVP-3000 microwave profiler observes sky brightness in 12 frequencies ranging from 22 to 60 GHz. This covers the water vapor line at 22.23 GHz and an O_2 absorption band in 50-70 GHz (V band). Multi-channel observation from the Radiometrics instrument is used for retrieving the temperature profile. A brief description of the temperature profile retrieval from radiometer measurements is given below. Various methods are described in detail in Solheim et al. (1998).

The relation between brightness temperature measurements represented by an M-dimensional measurement vector *y*, and the quantities to be retrieved by the N-dimensional profile vector *x*, may be expressed as

$$y = F(x) \tag{1}$$

which is, in general, nonlinear. The retrieval process solves the above equation and derives profile *x* from measurement *y*. Since there are more numbers of unknowns than the number of linearly independent observations, a unique solution does not exist. The Neural Network method used by Solheim et al (1998) obtains additional information about *x* from a statistical ensemble of a large number of historic radiosonde databases at a given location. Plots of the radiosonde observations during April 1999 at the Mount Washington site and the corresponding retrieved atmospheric profiles using the neural network method can be found in Ware (2000). But radiosonde datasets are not available at many locations and at various times. Hence, the neural network-based inversion method has only a limited application.

An alternate approach, namely an analytical method based on simplified physical models does not depend upon geophysical location, but oversimplifies the detailed description of atmospheric structure. It is difficult, if not impossible, to take many physical processes and variables into account while constructing analytical methods. The problem becomes intractable analytically. One advantage of the physically-based method is that of offering insights to the physical processes*. In this paper we propose a physically-based method to obtain i) the t of strength of the temperature inversion near the ground, and ii) the height of inversion layer under non-precipitating conditions.* We selected only two frequencies in our method because they specify the necessary and sufficient conditions for a closed-form solution when only two parameters have to be retrieved.

4. SENSITIVITY STUDY

Even under clear sky conditions, temperature inversions at 0.5-1.5 km from the ground are observed. So in this part of the paper, we investigate the sensitivity of down-welling brightness temperature T_b measurements in 20-30 GHz and 50-60 GHz to temperature inversions. Selected frequencies for our study are: 22.235, 23.035, 28.835, 26.235, 30.0, 51.25, 52.28, 53.85, 54.94, 56.66, 57.29 and 58.8 GHz, a total of 12 frequencies that coincide with the TP/WVP-3000 radiometer frequencies. The chosen atmospheric parameters are: ground pressure P_0 = 840mb, ground temperature T_g = 280^o, pressure scale height = 7 km, amount of vapor = 1.0 cm, height of atmosphere = km and cosmic background brightness temperature = 2.7^o K.

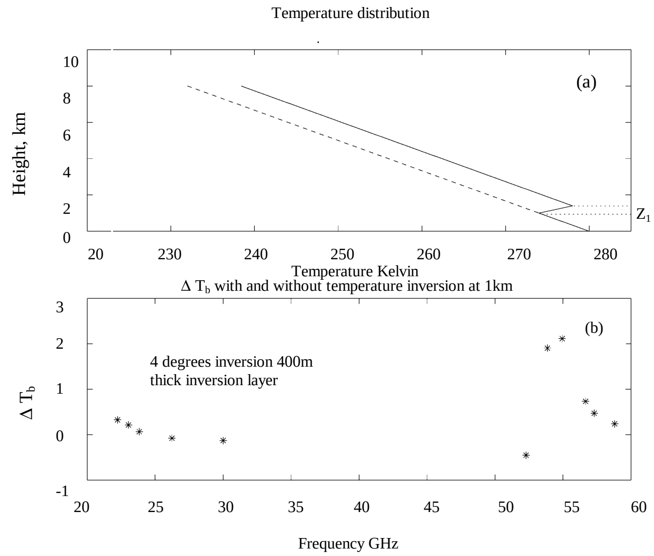

Figure 1: (a): Temperature distribution with height in the atmosphere for two different atmospheric models. Z_1 and Z_2 refer to the height at the bottom and top of the inversion layer. (b): The difference in down-welling brightness temperature between temperature inversion in the atmosphere and constant decrease in temperature in the atmosphere.

The temperature distribution is characterized by two models: a) a temperature lapse rate of 6.0^o K per km with no inversion, b) a temperature inversion of 4^o K at 1 km above the ground with an inversion layer thickness of 400 m and c) a temperature lapse rate of 6^o per km.

The assumed temperature profiles are shown in Fig. 1a. The down-welling brightness temperature difference *(ΔT_b)* due to the inclusion of or exclusion of temperature inversion at various frequencies are shown in Fig. 1b. The absorption of gases in the atmosphere was calculated using the Rosenkranz absorption model (1998). The down-welling brightness temperature was calculated using the NCAR microwave radiation transfer program. From the figure, it can be clearly seen that radiation at 53.85 and 54.94 GHz show the maximum sensitivity to temperature inversion in the atmosphere. Hence these two frequencies are selected for further analysis. The radiation at these frequencies is sensitive to other physical parameters such as pressure scale height, water vapor and cloud liquid. For the present, these quantities are kept constant.

5. RETRIEVAL METHOD

5.1 Taylor series method

The brightness difference in down-welling brightness temperature between an atmosphere with constant lapse rate and the atmosphere with temperature inversion can be expressed in the Taylor series as,

$$\Delta T_b = \frac{\partial T_b}{\partial T_{inv}} \Delta T_{inv} + \frac{\partial T_b}{\partial z_1} \Delta Z_1 + \frac{\partial^2 T_b}{\partial T \partial z_1} \Delta T_{inv} \Delta Z_1 + \ldots \quad (2)$$

where Z_1 is the height of inversion layer and T_{inv} is the temperature inversion in a layer of specified thickness. To start with, a simplified model where all the other atmospheric parameters like the initial lapse rate, the lapse rate above the inversion layer and the thickness of the layer are assumed to be known. We used the following parameters for the present study: the temperature lapse rate above and below the inversion layer are fixed at 6^o K km^{-1}; the inversion layer thickness is 0.4 km; the ground temperature is 280^o K; the ground pressure is 840 mb; and the pressure scale height is 7 km. These are some of the typical values of the observed parameters. The transfer equation was solved for clear sky conditions with and without temperature inversion for various Z_1*s* and ΔT_{inv}*s* to find the sensitivity of T_b to these parameters following a procedure outlined in Li et al (1997). Two simultaneous nonlinear equations were derived from model calculations using regression fits for ΔT_b.

$$\Delta T_B^{54} = (\alpha_0 \Delta T_{inv} + \alpha_1)\Delta T_{inv} + (b_0 \Delta Z_1^4 + b_1 \Delta Z_1^3 + b_2 \Delta Z_1^2 + b_3 \Delta Z_1 + b_4)\Delta Z_1 + (c_0 + c_1 \Delta Z_1 + c_2 \Delta T_{inv})\Delta Z_1 \Delta T_{inv} \quad (3)$$

$$\Delta T_B^{55} = \alpha_0 \Delta T_{inv} + \alpha_1)\Delta T_{inv} + (b_0 \Delta Z_1^4 + b_1 \Delta Z_1^3 + b_2 \Delta Z_1^2 + b_3 \Delta Z_1 + b_4)\Delta Z_1 + (c_0 + c_1 \Delta Z_1 + c_2 \Delta T_{inv})\Delta Z_1 \Delta T_{inv} \quad (4)$$

The coefficients can be found in Table 1. The quantities *t* and *z* denote the difference in temperature inversion from a base state value of *3^o K* and *Z* is the difference in height of the inversion layer above the base state height of 0.3 km.

Coefficients	Frequency	
	54 GHz	55 GHz
a_o	0.0008	-0.0002
a_1	0.3837	0.4891
b_o	-0.0034	-0.0172
b_1	0.0215	0.1165
b_2	-0.0965	-0.4550
b_3	0.3849	1.3517
b_4	-1.2872	-2.9725
c_o	-0.2095	-0.4812
c_1	0.0796	0.2420
c_2	-0.0002	0.0001

Table 1. Numerical values of coefficients for Eqs (3) and (4). Radiation transfer model is used for computing the coefficients.

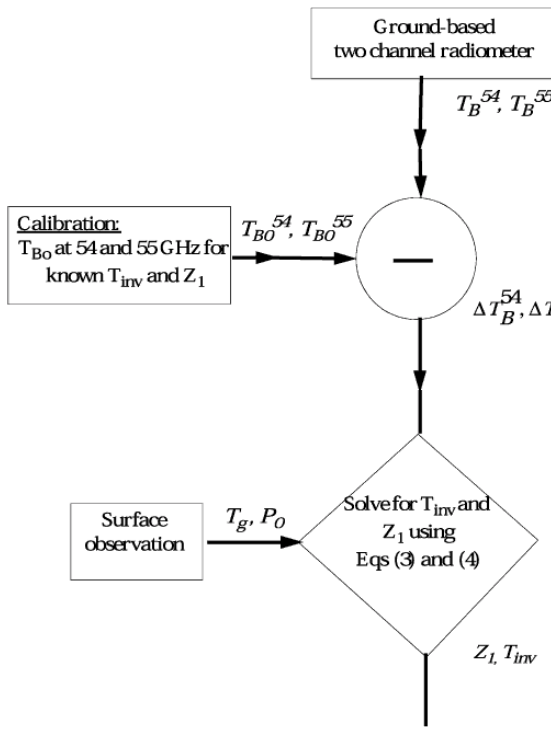

Figure 2: Flow chart of the retrieval algorithm

The base state value of T_b is assumed to be known. In practical applications, a calibration of this base state has to be made. A flowchart depicting the retrieval method is shown in Fig. 2. The above nonlinear equations (3) and (4) are solved using the Newton-Raphson iterative technique. The ΔT_b*s* are generated for various amounts of temperature inversion and heights of inversion. They become the input for the above equation. *Using our algorithm the height of inversion is retrieved with a standard deviation error of 0.1 km and the amount of inversion within 0.12^o K.*

The method was tested for various magnitudes of vapor and cloud liquid values and found to give reasonable retrievals. The range of these quantities studied is given in Table 2. *For total vapor 1.0cm and cloud liquid of 0.6mm in a layer of 1 km thickness at a height of 0.5km, the height of the inversion is retrieved with a standard deviation error of 0.11 km and the amount of inversion within 0.25^o K.* The retrieval of temperature inversion parameters in the presence of liquid cloud is less accurate compared to clear sky conditions. We find that the method is applicable only when the inversion layer is above 0.4km and the amount of temperature inversion is greater than *4^o K.*

Parameter	Value	Units
Height of temperature inversion	0.3	km
Amount of inversion	4.0	Kelvin

Table 2a: Base state of parameters used for computing the reference brightness temperatures T_{BO}^{54} and T_{BO}^{55}.

Parameter	Range	Unit
V	[0.5, 1.5]	cm
LWP	[0.0, 600.0]	g m^{-2}
Height of temperature inversion	[0.5, 1.5]	km
Amount of temperature inversion	[3.0, 8.0]	Kelvin
Surface temperature	280	Kelvin
Surface pressure	840	mb
Lapse rate	6.0	Kelvin

Table 2b. Atmospheric parameter used as an input to radiation transfer model for computing Table 1.

6. SUMMARY AND CONCLUSIONS

The proposed method is able to retrieve the height of the inversion with a standard deviation error of 0.1 km and the amount of inversion within 0.12^o K in clear sky conditions. Present limitations of the method are: the temperature lapse rate above and below the inversion layer is assumed, so also is the thickness of the inversion layer. The additional three parameters would involve the formulation of an additional three equations. Since TP/WVP-3000 does observe at three more frequencies in the oxygen band alone, it should be possible in principle to retrieve the other physical parameters. The method does not work well for temperature inversions less than 3^o K or heights less than 0.3 km. Also, retrieval method should consider the effects due to the measurement error in brightness temperature observations. Future studies would investigate the removal of limitations of the method, like extending the range of height of inversion by considering more terms in the series and/or by changing the base state.

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