Retrieval of Satellite Microwave Observation over Land Surface by One-Dimensional Variational Data Assimilation

Qunbo Huang[1,2,3(✉)], Bainian Liu[1,2], De Xing[1,2], Weimin Zhang[1,2], and Weifeng Wang[3]

[1] Academy of Ocean Science and Engineering, National University of Defense Technology, Changsha, Hunan, China
hqb09@163.com
[2] College of Computer, National University of Defense Technology, Changsha, Hunan, China
[3] Weather Center of PLA Air Force, Beijing, China

Abstract. The data assimilation of satellite microwave observations over the land surface is a worldwide problem. 1D-Var can retrieve the atmospheric parameters by physical constraints, which is a useful technology. In this paper, 1D-Var is used to study the retrieval of atmospheric profile and AMSU-A microwave brightness observations over the land surface. The experimental results show that the retrieved effect of near-surface channel needs to be further improved. However, the retrieved effect of channel 4–15 is very good, which proves that 1D-Var has its advantage in land surface data assimilation.

Keywords: 1D-Var · Land surface · Data assimilation · Retrieval

1 Introduction

The numerical weather forecast (NWP) is a typical initial/boundary values problem. Given the estimation of the current atmospheric state (initial values) and the appropriate surface and boundary conditions, the atmospheric model will be able to simulate/predict the atmosphere in the future. The purpose of data assimilation is to use all existing information to define an atmospheric/ocean state with a maximum possibility [1]. Variational method is an important tool in the field of data assimilation, which based on the basis of the statistical estimation theory in minimizing, solving the cost function to obtain the most accurate analysis of the real state of the atmosphere. Variational data assimilation is often classified as one-dimensional variational data assimilation (1D-Var), three-dimensional variational data assimilation (3D-Var) and four-dimensional data variational assimilation (4D-Var).

1D-Var is often used as a retrieval and pre-processing method due to its algorithmic simplicity and easy to control. Phalippou [2] used 1D-Var method to retrieve the humidity and temperature, surface wind speed, cloud water content and skin temperature. Aonashi [3] described the assimilation of SSM/I by retrieving the TCWV, using the 1D-Var as an intermediary to assimilate new satellite observations, which is in favor

F. Qiao et al. (eds.), *Recent Developments in Mechatronics and Intelligent Robotics*,
Advances in Intelligent Systems and Computing 690, DOI 10.1007/978-3-319-65978-7_60

of eliminating the illusive model precipitation in non-precipitated area. This method has the advantage of better controlling the response of observation operator to the variation of atmospheric state [4]. Huang studied the basic principles of the 1D+4D-Var two-step method and design a one+four-dimensional variational assimilation system process which is used for assimilating the cloud and rain affected Special Sensor Microwave/Imager (SSM/I) data [5]. Liu did some research about 1D-Var retrieval of 1D+4D-Var system, which builds cloud-effected microwave satellite data retrieval platform by adding super-saturation penalty part in cost function and super-saturation checking in background profiles [6]. Huang et al. analyzed the algorithm which is used to retrieve cloud parameters based on the 1D-Var scheme, this approach suits best for the advanced infrared sounders such as AIRS [7].

This paper presents a method of retrieving satellite brightness temperature, atmospheric temperature and humidity profiles. We focus on the simulation of profile over land surface, investigate the possibility of data assimilation of satellite data on land surface by 1D-Var. Section 2 describes the algorithm process of 1D-Var. Section 3 describes the experiment configure. Section 4 shows and analyzes some experimental results of the brightness temperature, atmospheric retrieval. Finally, conclusions and plans for future work provide in Sect. 5.

2 1D-Var Algorithm

The principle of 1D-Var is similar to other variational data assimilation algorithms (such as 3D/4D-Var), but 1D-Var is generally considered as an inversion problem, and 3D/4D-Var is generally referred to as an analysis process. According to Bayesian theory and assuming that the background error is not dependent to the observation error, and the errors are Gaussian distribution, the solution to one-dimensional variational problem can be expressed as the minimization of the cost function:

$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x} - \mathbf{x}_b)^T \mathbf{B}^{-1}(\mathbf{x} - \mathbf{x}_b) + \frac{1}{2}\left[\mathbf{y}^0 - H(\mathbf{x})\right]^T \mathbf{R}^{-1}\left[\mathbf{y}^0 - H(\mathbf{x})\right] \tag{1}$$

where $\mathbf{x}_b$ is background profiles, $\mathbf{B}$ and $\mathbf{R}$ are the background error covariance matrix and observation error covariance matrix, $\mathbf{y}$ is satellite observation. $H(\mathbf{x})$ represents the radiance which is simulated by the forward model of RTTOV11, where $\mathbf{x}$ is the input parameters of RTTOV11.

According to the theory of functional analysis, the analytical $\mathbf{x}_a$ value should satisfy the gradient Eq. (2), which is acquired by minimizing the difference between background and observation radiance.$\mathbf{x}$ has the optimal solution when $J(\mathbf{x})$ achieves minimum.

$$\nabla J(\mathbf{x}) \rightarrow 0 \tag{2}$$

A simple linear solution of the 1D-Var is shown in the Eq. (3), where the second term on the right side of the equation exists as a correction term, and it can be seen that the retrieved profile is the sum of the background profile and the correction term. So then the error covariance can be further quantified by 1D-Var retrieval in Eq. (4), which has obviously improved effect on the background field information.

$$\mathbf{x}a = \mathbf{x}b + [\mathbf{HB}]^T[\mathbf{HBH}^T + \mathbf{R}]^{-1}(\mathbf{y} - \mathbf{H}(\mathbf{x}b)) \tag{3}$$

$$\mathbf{S}_a = \mathbf{B} - [\mathbf{HB}]^T[\mathbf{HBH}^T + \mathbf{R}]^{-1}\mathbf{HB} \tag{4}$$

The whole flow of one-dimensional variational data assimilation algorithm is shown in Fig. 1. It is shown that, before the satellite microwave observations are introduced into the 1D-Var system, the scan bias correction, pre-screening, bias correction and other pre-processing process should be made to revise the observation error, and then the departures between the simulated background field observation and the real observations are obtained. The departures are used for two purposes, one for calculating the analysis field and the other is for the calculation of the adjoint model to obtain the updated model field, and continuing to input to the observation operator until achieves the accuracy condition we pre-set.

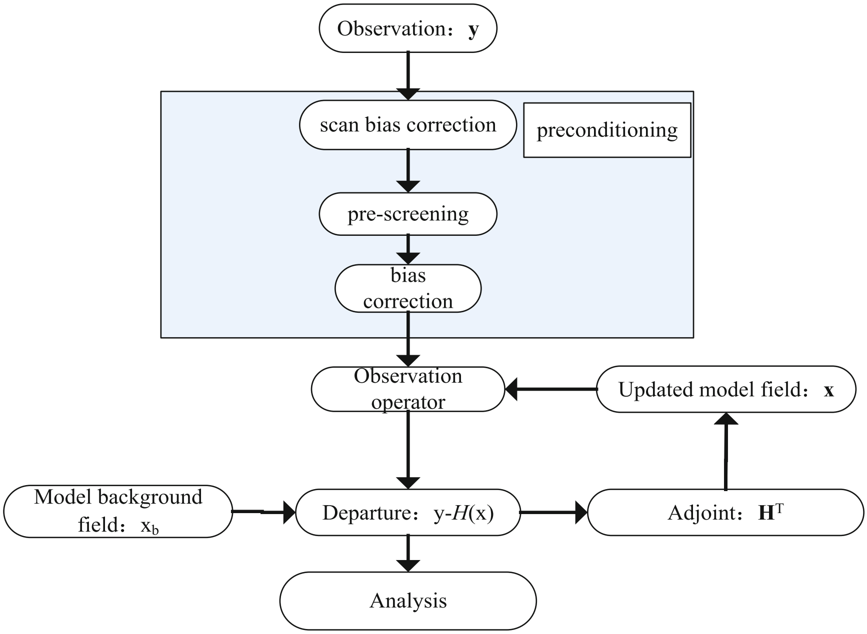

Fig. 1. The flow of 1D-Var

3 Experiment Configure

The data used in this paper are AMSU-A brightness data, the US Center for Environmental Prediction (NCEP) 6-hour forecast data are used as the background grid field. In this paper, we choose the Radiative Transfer Model for TOVS (RTTOV11) as the forward model operator to simulate the brightness temperature. At the same time, US standard atmospheric profile is used to generate true profile with 54 levels. The related data of the variables are shown in Table 1.

Table 1. The variables related to the observation and background field

Variable	Content	Unit
Instrument	AMSU-A	/
First channel	1	/
Last channel	15	/
Date	2014.07.23	/
Surface type	Land	/
Latitude	15.6747S	Degree
Longitude	127.9980E	Degree
Satellite zenith angle	44.650	Degree

The AMSU-A contained 15 channels, and there are 13 temperature detection channels and 2 window/surface channels, Fig. 2 shows the weight functions of AMSU-A channels. Each curve represents the sensitivity of a specific channel to the different levels of atmosphere. It can be clearly seen from the figure that the peak energy contribution layer of the window channels 1–3 and 15 comes from the surface and the peak energy contribution layers of channels 4–14 are the heights of the surface to 60 km, respectively. These curves are calculated by using the US standard atmospheric profile [8].

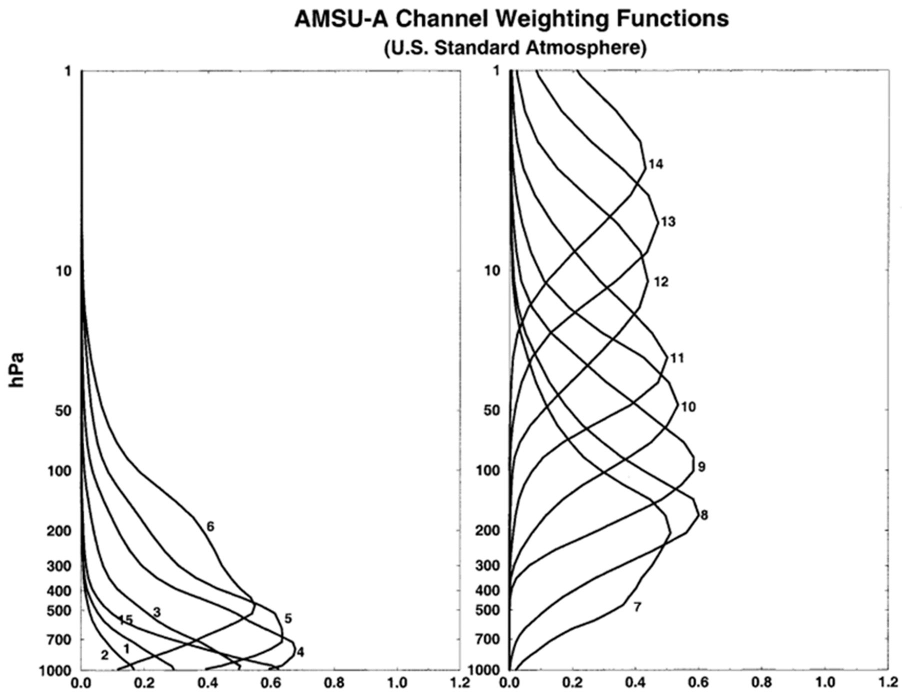

Fig. 2. AMSU-A weight functions of 15 channels [9].

4 Experimental Results

4.1 The Effect of Simulated Observation

We firstly check the effect of forward simulated background brightness temperature and the retrieved brightness temperature by 1D-Var. Figure 3a shows the simulated background brightness temperature (blue line) and 1D-Var retrieved brightness temperature (green line) are very close to the real observation (red line) for the full 15 channels. This suggests that 1D-Var system works well, and the simulation and retrieval accuracy are both high.

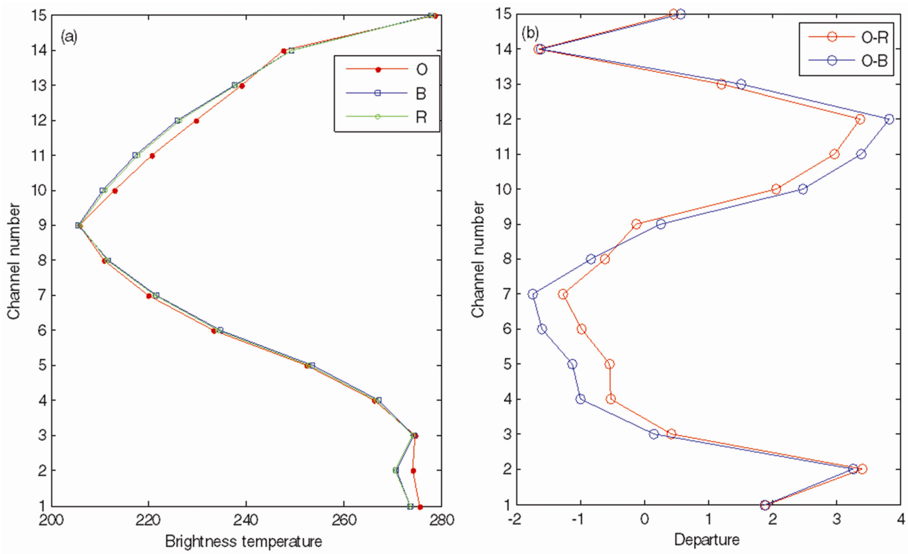

Fig. 3. (a) Comparison among the simulated background brightness temperature (blue line), 1D-Var retrieved brightness temperature (green line) and real observation (red line) for the full 15 channels. (b) Comparison between the background departure (blue line) and retrieval departure (red line). (Color figure online)

Figure 3b gives a comparison of the background departure (observations minus the background brightness, blue line) and retrieval departure (observations minus the 1D-Var retrieved brightness temperature, red line). Retrieval departures are worse than background departures for channels 1–3, mainly because these channels are relatively close to the surface and affected by the surface is relatively large, resulting in background error and observation error is relatively large. While the channels 4–15 retrieved effect is better. As can be seen from Fig. 2, AMSU-A channels 1–5 are more sensitive to the surface, only the channels above channel 5 can be implemented active assimilation in many operational data assimilation centers in the world. This result shows that 1D-Var has the positive potential to assimilate the satellite microwave observations over land surface.

4.2 The Effect of Simulated Atmospheric Profile

Subsequently, we also analyze the background departure (background profile minus true profile) and the retrieval departure (1D-Var retrieved profile minus true profile). Figure 4a and b shows the temperature departure and humidity departure respectively. For the Y axis of the both figures, the larger pressure values are more close to the land surface. In the middle atmosphere (about 700 hPa ~ 300 hPa), the temperature retrieval effect is good because of the influence of land surface is not too large. On the contrary, there is a large difference between the background and the retrieval departure due to the improved surface emissivity leads to a better retrieved atmospheric profile.

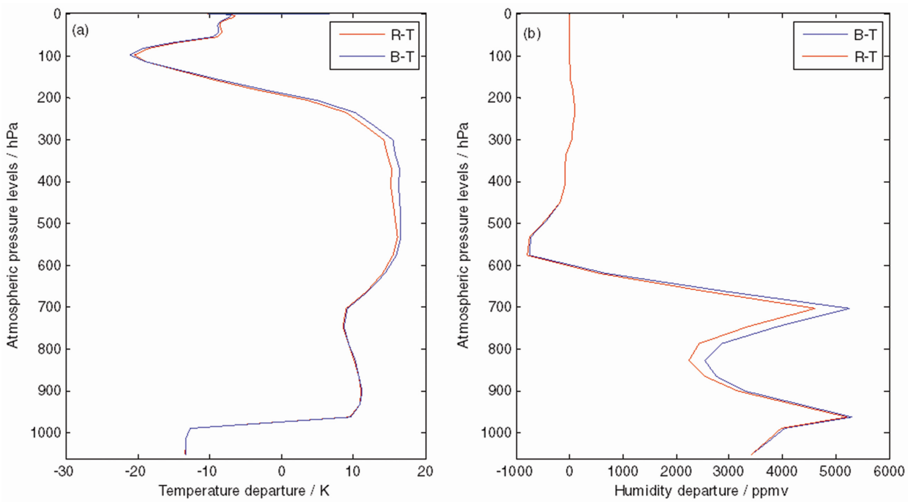

Fig. 4. Comparison the background departure (blue line) and the retrieval departure (red line) of the temperature (a) and humidity (b) profile at 54 atmospheric pressure levels. (Color figure online)

5 Conclusion

Based on the one-dimensional variational data assimilation technology, we try to retrieve the atmospheric profile and microwave brightness temperature over the land surface. It has the advantage of constraining the state variables physically and maintaining physical balance between state variables. The experimental results show that the 1D-Var system works well and the effect of brightness temperature retrieval and atmospheric profile retrieval are ideal. However, because of the difficulty in obtaining accurate surface emissivity, the retrieval quality of brightness temperature of the near surface channels still needs to be further improved. Next, we will conduct global area with various types of land surface to retrieve, and introduce observations of new microwave instruments to test the potential of the 1D-Var system.

Acknowledgements. The work was supported by the Natural Science Foundation of China (Grant No. 41375113).

References

1. Talagrand, O.: Assimilation of observations, an introduction. J. Meteorol. Soc. Jpn. **75**, 191–209 (1997). (Special Issue)
2. Phalippou, L.: Variational retrieval of humidity profile, wind speed and cloud liquid-water path with the SSM/I: potential for numerical weather prediction. Q. J. Roy. Meteorol. Soc. **122**, 327–355 (1996)
3. Aonashi, K., Shibata, A.: The impact of assimilating SSM/I precipitable water and rain flag data on humidity analysis and short-term precipitation forecasts. J. Meteorol. Soc. Jpn. **74**(1), 77–99 (1996)
4. Eyre, J.R., Kelly, G.A., Mcnally, A.P., et al.: Assimilation of TOVS radiance information through one-dimensional variational analysis. Q. J. Roy. Meteorol. Soc. **119**(514), 1427–1463 (1993)
5. Huang, Q.B.: A variational data assimilation technology of the cloud and rain affected satellite microwave data. National University of Defense Technology (2011)
6. Liu, Y.L.: Application research of 1D-Var retrieval technology in cloud- and precipitation-effected satellite microwave observation data assimilation. National University of Defense Technology (2013)
7. Huang, Q.B., Zhang, W.M., Yu, Y.: A cloud parameters retrieval algorithm in the variational assimilation system. In: The 2nd International Conference on Computer Application and System Modeling, pp. 0599–0602 (2012)
8. Ma, G.: A study on assimilation of radiance from FY3's atmospheric vertical sounder system. LanZhou University (2008)
9. Li, J., Wolf, W.W.: Global soundings of the atmosphere from ATOVS measurements: the algorithm and validation. J. Appl. Meteorol. **39**(8), 1248–1268 (2000)