Use of double channel differences for reducing the surface emissivity dependence of microwave atmospheric temperature and humidity retrievals

X. Cui\textsuperscript{1,2}, Z. Yao\textsuperscript{2}, Z. Zhao\textsuperscript{2}, Y. Zhai\textsuperscript{2}, Z. Sun\textsuperscript{2}, W. Cheng\textsuperscript{2}, and C. Gu\textsuperscript{2}

\textsuperscript{1}State Key Laboratory of Geo-Information Engineering, China
\textsuperscript{2}Beijing Institute of Applied Meteorology, China

Corresponding author: Z. G. Yao (yzg_biam@163.com)

Key points:
\begin{itemize}
  \item We propose a microwave temperature and humidity retrieval scheme based on double channel differences.
  \item We show the accuracy performance of the double channel differences retrieval scheme for AMSU-A/MHS measurements.
  \item Results demonstrate significant performance improvement over traditional AMSU-A/MHS neural network retrieval scheme.
\end{itemize}

Abstract

Surface emissivity has a significant impact on atmospheric parameter retrievals. To reduce the dependence of retrievals on surface emissivity, a double channel differences equation is deduced, and a corresponding retrieval scheme is constructed. Retrieval experiments are performed using Advanced Microwave Sounding Unit-A (AMSU-A) and Microwave Humidity Sounder (MHS) simulation and global measurement data. Simulation experiments show that the double channel differences scheme can reduce the root mean square error (RMSE) of the temperature and humidity profiles in the middle and lower atmosphere. Retrieval experiments based on AMSU-A and MHS global measurements show that the double channel differences scheme can significantly reduce the RMSE of temperature profiles in the lower atmosphere and humidity profiles in the middle and lower atmosphere for cloudy and cloudless conditions, different surface types, and different scan angles, with maximum reduction values of 0.64K and 9.03%, respectively. Regarding RMSE improvement, that of the cloudy condition is greater than that of the cloudless condition, that of the land is greater than that of the coast and the sea, and there is no significant dependence on the scan angle. The double channel differences scheme is very sensitive to initial near-surface temperature. Reducing the initial near-surface temperature error can significantly improve the temperature retrieval accuracy below 900 hPa, with maximum reduction value of 3.25K. In addition, reducing the initial profiles and the near-surface temperature and
humidity errors can improve temperature and humidity retrieval accuracy, but the retrieval results are relatively insensitive to these factors.

Plain language summary
Microwave vertical detectors such as AMSU-A/MHS provide the unique ability to acquire global atmospheric temperature and humidity profiles. However, at present, their ability to acquire temperature and humidity information in the lower atmosphere has not been fully exploited, mainly due to the influence of surface emissivity. Therefore, reducing the influence of surface emissivity is a key. In this paper, a temperature and humidity profiles retrieval scheme is constructed by using the relationship between the surface emissivity of adjacent channels. The research shows that the scheme can significantly improve temperature and humidity retrieval accuracy for cloudy and cloudless conditions, different surfaces types, different scan angles. Reducing initial values error in the scheme can further improve retrieval accuracy.

Index terms and keywords: microwave surface emissivity, atmosphere temperature and humidity profiles, double channel differences scheme, AMSU-A, MHS

1 Introduction
Microwave vertical detectors has been widely used in atmospheric parameter retrieval and data assimilation (Aumann et al., 2003; He et al., 2011; He et al., 2018; Li et al., 2000; Milstein & Blackwell, 2016; Zhigang et al., 2005), but the results of retrieval and assimilation in the lower atmosphere are generally poor (He et al., 2011; Karbou et al., 2005a; Zou et al., 2013). The reason is mainly due to the influence of surface emissivity. For the lower atmosphere channel, it is difficult to extract the atmospheric temperature and humidity information from the measurements due to the surface emissivity dependence. To reduce the influence of surface emissivity, non-lower atmosphere channels are usually given priority in atmospheric parameter retrieval or assimilation applications (He et al., 2011; Weng, 2007; Zou et al., 2013).

When the lower atmosphere channels are used for the atmospheric parameters retrieval and assimilation, surface emissivity is commonly used as known input parameters (Karbou et al., 2005a; Weng et al., 2012; Zou et al., 2013. For example, Karbou et al. (2005a) used satellite measurements to precalculate the surface emissivity for use in atmospheric parameter retrieval. He et al. (2011) calculated surface emissivity using the Community Radiative Transfer Model (CRTM) and analyzed the effects of the 4th and 5th channels of AMSU-A on assimilation performance. He et al. (2018) and Aires (2018) corrected the observed brightness temperature based on the precalculated surface emissivity to reduce the retrieval errors of the temperature and humidity profiles. Although the precalculated surface radiance is favorable for the improvement of retrieval and assimilation accuracy, the surface emissivity, which changes significantly over time and space, is difficult to accurately obtain over the global (Karbou et al., 2005b). Moreover, most of the existing emissivity studies are focusing on clear-sky cases (Tian et al., 2015). Thus, reducing the surface emissivity dependence of microwave atmospheric parameter retrieval is urgent.

To reduce the dependence of the atmospheric parameter retrievals on surface emissivity, this paper proposes a microwave temperature and humidity profiles retrieval scheme based on double channel differences, and validates the scheme by using AMSU-A/MHS simulation and global measurement data. The second chapter of this paper deduces the double channel differences equation. The third chapter introduces the data and methods.
The fourth chapter presents the simulation experiment. The fifth chapter presents the retrieval application experiment. The sixth chapter is the summary and discussion.

2 Basic principles

The microwave radiation transfer equation can be expressed as

\[ I = \varepsilon I_s + I_s + I_u \]  
(1a)

\[ I_s = B_s \tau_p \]  
(1b)

\[ I_u = (1 - \varepsilon) \tau_s \int_{\ln p_s}^{\ln p_{\infty}} B \frac{\partial \tau}{\partial \ln p} d \ln p \]  
(1c)

\[ I_s = \int_{\ln p_s}^{\ln p_{\infty}} B \frac{\partial \tau}{\partial \ln p} d \ln p \]  
(1d)

where \( I \) represents the radiation measured by the sensor. \( I_s, I_u \) and \( I_u \) are the skin and atmospheric downwelling and upwelling radiation, respectively. \( \varepsilon \) is the surface emissivity. \( B_{s, u} \) and \( B \) are the surface and each layer Planck radiation, respectively. \( \tau_p, \tau_s \) and \( \tau \) are surface to space, pressure layer to surface, and pressure layer to space atmospheric transmittance, respectively.

The weight function (K) of equation (1) is:

\[ K = \frac{\partial \tau}{\partial \ln p} \]  
(2)

The surface emissivity of a single channel varies significantly with time and space (Karbou et al., 2005b), whether there is a certain correlation between the surface emissivity of adjacent channels; thereby equation (1) can simplify the surface emissivity item and facilitate temperature and humidity profiles retrieval to become the key. For various surface types, Karbou et al. (2005b) showed that the most difference between the mean surface emissivity of adjacent channels is less than 0.02 in 23.8 GHz, 31.4 GHz and 50.3 GHz, 50.3 GHz and 89 GHz, and 89 GHz and 150 GHz. Moncet et al. (2011) analyzed the surface emissivity change between 6.925 GHz, 10.65 GHz, 18.7 GHz, 23.8 GHz, 36.5 GHz and 89 GHz for horizontal and vertical polarization, and the difference is approximately 0.01. Yan and Weng (2011) showed that the difference between the mean surface emissivity of different desert types between 23.8 GHz, 31.4 GHz, 50.3 GHz and 89 GHz was basically less than 0.01. Although the current study does not fully explain the surface emissivity changes of adjacent channels on all surface types, the above studies show that there is a certain correlation between the surface emissivity change trend of adjacent channels. In addition, compared with the surface emissivity of each channel (land: ~0.9; sea: ~0.5), the difference of adjacent channels is small, which provides the condition for reducing the influence of surface emissivity. The surface emissivity of each channel can be expressed as
\[ \varepsilon_i = \varepsilon_j + \delta \varepsilon \]  

(3)

where \( \varepsilon_i \) and \( \varepsilon_j \) are the surface emissivity of adjacent channels, respectively. \( \delta \varepsilon \) is the difference of surface emissivity of adjacent channels as a function of time and space.

The microwave radiation transfer equation (1) of different channels can be expressed as

\[
\begin{align*}
I_i &= (\varepsilon_j + \delta \varepsilon)I_{s,j} + I_{s,j} + I_{\tau,j} \\
I_j &= \varepsilon_i I_{s,i} + I_{s,j} + I_{\tau,j}
\end{align*}
\]  

(4)

The subscripts \( i \) and \( j \) represent different channels. The equation of channels \( i \) and \( j \) are multiplied by \( I_s \) of the other channel as follows:

\[
\begin{align*}
I_i I_{s,j} &= (\varepsilon_j + \delta \varepsilon)I_{s,i} I_{s,j} + I_{s,j} I_{s,i} + I_{\tau,j} I_{s,i} \\
I_j I_{s,i} &= \varepsilon_i I_{s,i} I_{s,j} + I_{s,j} I_{s,i} + I_{\tau,j} I_{s,i}
\end{align*}
\]  

(5)

Simplify the equations (5):

\[
\begin{align*}
I_i I_{s,j} I_{s,i} &= \delta \varepsilon I_{s,i} I_{s,j} + (I_{s,j} I_{s,j} - I_{s,j} I_{s,i}) + (I_{\tau,j} I_{s,j} - I_{\tau,j} I_{s,i}) \\
I_j I_{s,j} I_{s,i} &= \delta \varepsilon I_{s,i} I_{s,j} + (I_{s,j} I_{s,j} - I_{s,j} I_{s,i}) + (I_{\tau,j} I_{s,j} - I_{\tau,j} I_{s,i})
\end{align*}
\]  

(6)

Equation (6) is the double channel differences equation. It can be seen that the radiation on the left side of equation (6) (recorded as \( I_d \)) is composed of the sensor measurement radiation \( (I_i, I_j) \) and the skin radiation \( (I_{s,i}, I_{s,j}) \). In the actual retrieval application, \( I_{s,i} \) and \( I_{s,j} \) are first calculated and combined with \( I_i \) and \( I_j \) to calculate \( I_d \), and \( I_d \) is used to retrieve the temperature and humidity profiles.

The weight function of equation (6) is:

\[
K_d = \tau_{p,i} \frac{\partial \tau_i}{\partial \ln p} - \tau_{p,j} \frac{\partial \tau_j}{\partial \ln p}
\]  

(7)

3 Data and methods

3.1 The data

At present, the on-orbit operation microwave atmospheric vertical detector mainly includes Advanced Microwave Sounding Unit-A (AMSU-A), Microwave Humidity Sounder (MHS), Advanced Technology Microwave Sounder (ATMS), Microwave Temperature Sounder (MWTS) and Microwave Humidity Sounder (MWHS). AMSU-A and MHS loaded on NOAA and METOP satellites have been widely used. This paper carries out retrieval research with the AMSU-A and MHS loaded on METOP-B. Channel characteristics for both AMSU-A and MHS radiometers are given in Table 1. Figure 1 shows the weighting function distributions for all AMSU-A and MHS channels calculated for a 51-level reference profile of Radiation Transfer for TOVS(RTTOV) at nadir.
Table 1. AMSU-A and MHS channel description.

| Channel No | Frequency (GHz) | Noise equivalent temperature difference (K) | Resolution at nadir (km) |
|------------|-----------------|---------------------------------------------|-------------------------|
| AMSU-A     |                 |                                             |                         |
| 1          | 23.8            | 0.30                                        | 48                      |
| 2          | 31.4            | 0.30                                        | 48                      |
| 3          | 50.3            | 0.40                                        | 48                      |
| 4          | 52.8            | 0.25                                        | 48                      |
| 5          | 53.596±0.115    | 0.25                                        | 48                      |
| 6          | 54.4            | 0.25                                        | 48                      |
| 7          | 54.9            | 0.25                                        | 48                      |
| 8          | 55.5            | 0.25                                        | 48                      |
| 9          | 57.290 (fo)     | 0.25                                        | 48                      |
| 10         | fo±0.217        | 0.40                                        | 48                      |
| 11         | fo±0.3222±0.048 | 0.40                                        | 48                      |
| 12         | fo±0.3222±0.022 | 0.60                                        | 48                      |
| 13         | fo±0.3222±0.010 | 0.80                                        | 48                      |
| 14         | fo±0.3222±0.0045| 1.20                                        | 48                      |
| 15         | 89              | 0.50                                        | 48                      |
| MHS        |                 |                                             |                         |
| 1          | 89              | 0.23                                        | 16                      |
| 2          | 157             | 0.37                                        | 16                      |
| 3          | 183.31 ± 1      | 0.55                                        | 16                      |
| 4          | 183.31 ± 3      | 0.42                                        | 16                      |
| 5          | 190.31          | 0.35                                        | 16                      |
AMSU-A and MHS weighting functions for a 51-level reference profile of RTTOV at nadir.

The simulation experiment used the sampled databases of 60-level atmospheric profiles (60L-SD) issued by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Chevallier, 2001). The profiles in the 60L-SD are selected from the ECMWF 40-year re-analysis (ERA-40). The database has a total of 13495 profiles, and gathers profiles corresponding to various sea conditions as well as to land conditions, including high elevated grounds. The 6790 profiles with surface pressure greater than 1000hPa in 60L-SD are used in this paper (recorded as 60L-SD choose). Figure 2 shows the statistics of the 60L-SD choose database and 60L-SD database.
Figure 2. (a)-(d) statistics of the 60L-SD database, (e)-(h) statistics of the 60L-SD choose database. The blue solid line and dotted line represent the average and average plus or minus one standard deviation, respectively. The green solid line and dotted line represent the median and the lower and upper quartiles, respectively. Red solid line represents the temperature and humidity distribution at 1050hPa.
The retrieval application experiment uses the global AMSU-A and MHS L1B products of the METOP-B satellite obtained from European Meteorological Satellite (EUMETSAT). The Infrared Atmospheric Sounding Interferometer (IASI) on the METOP-B satellite is synchronized with AMSU-A and MHS, and the IASI Atmospheric Temperature Water Vapour and Surface Skin Temperature product (IASI L2) is used to identify areas for cloudy and cloudless conditions. The target profiles are reanalysis data (ERA-Interim) issued by ECMWF at 0.5° × 0.5°, four times per day, and 37 layers in the vertical direction.

3.2 Channel selection

To reduce the dependence of retrievals on surface emissivity, it is preferred to select observation channels that are significantly affected by the surface emissivity. It can be seen from Figure 1 that Channel No 1–6 and 15 in are significantly affected by the surface emissivity. For the MHS detection channel, since the number of channels is small, all channels are selected. Based on equation (6), this paper selects Channel No 1–6 and 15 in AMSU-A and 1–5 in MHS to construct new channels and the large numbers of new channels are constructed. To simplify the retrieval algorithm and neural network, the equation (7) is used to select the new channels with the peak of the weight function at different heights and the maximum peak value at the same height as the channels that are used for double channel differences scheme temperature and humidity profiles retrieval. To further reduce the lower atmospheric temperature retrieval error, the three channels with the weight function peak at 1000hPa (New Channel No 2, 3, and 4 in Table 2) are used as the new channels for retrieval. Tables 2 and 3 show the new channels constructed by the AMSU-A and MHS channels, respectively. Figure 3 shows the new channel weighting functions in Tables 2 and 3.

**Table 2.** New channels constructed by AMSU-A channels.

| New Channel No | The AMSU-A channels used in construction | New Channel No | The AMSU-A channels used in construction |
|----------------|----------------------------------------|----------------|----------------------------------------|
| 1              | 1, 3                                   | 6              | 1, 5                                   |
| 2              | 1, 4                                   | 7              | 3, 5                                   |
| 3              | 2, 4                                   | 8              | 1, 6                                   |
| 4              | 4, 15                                  | 9              | 4, 6                                   |
| 5              | 3, 4                                   |                |                                        |

**Table 3.** New channels constructed by MHS channels.

| New Channel No | The MHS channels used in construction |
|----------------|---------------------------------------|
| 1              | 1, 2                                  |
| 2              | 1, 3                                  |
| 3              | 1, 4                                  |
| 4              | 1, 5                                  |
3.3 Forward calculation method

The radiative transfer model used in this paper is RTTOV 10.2 (Hocking et al., 2011), which is officially released by the EUMETSAT Satellite Application Facility on Numerical Weather Prediction (NWP SAF) and contains coefficient files suitable for the AMSU-A and MHS channels.

To analyze the influence of different precision $I_\lambda$ on the retrieval performance, the initial temperature and humidity profiles and the near-surface temperature and humidity with different precision are used as the double channel differences scheme inputs by the calculation of $I_\lambda$. Inputs for schemes 2, 3, and 4 are shown in Table 4.

| Retrieval | Scheme | Scheme 1 retrieval of temperature and humidity profiles | Scheme 1 retrieval of near-surface temperature and humidity | ERA-Interim temperature and humidity profiles | ERA-Interim near-surface temperature and humidity |
|-----------|--------|-------------------------------------------------------|----------------------------------------------------------|---------------------------------------------|-------------------------------------------------|
| Temperature | scheme 2 | yes | yes | no | no |
| scheme 3 | yes | no | no | yes |
| scheme 4 | no | no | yes | yes |
| Humidity | scheme 2 | yes | yes | no | no |
| scheme 3 | yes | no | no | yes |
| scheme 4 | no | no | yes | yes |
3.4 Retrieval method

\( I_s \) is calculated from the temperature and humidity profiles, the near-surface temperature and humidity, and the surface temperature, but these factors except the surface temperature are the quantities to be retrieved. Therefore, to calculate \( I_s \), the initial temperature and humidity profiles and the initial near-surface temperature and humidity are first retrieved by the AMSU-A and MHS channels (scheme 1).

For different temperature and humidity profiles retrieval methods, Zhigang et al. (2005) showed that the retrieval accuracy of neural network (NN) is comparable to traditional physical iterative methods. To facilitate verification of the retrieval performance of the double channel differences scheme, this paper uses NN to retrieve temperature and humidity profiles.

For temperature retrieval, scheme 1 uses 15 channels of AMSU-A as inputs; schemes 2, 3, and 4 use 15 channels of AMSU-A and 9 channels of Table 2 as inputs. For humidity retrieval, scheme 1 uses 15 channels of AMSU-A and 5 channels of MHS as inputs; schemes 2, 3, and 4 use 15 channels of AMSU-A, 5 channels of MHS, 9 channels of Table 2, and 4 channels of Table 3 as inputs. To facilitate calculation of \( I_s \), the outputs of NN are 51 levels that are the same as the 51-level reference profile of RTTOV. The NN contains a single hidden layer. Table 5 shows the NN structures corresponding to different schemes.

**Table 5. Different schemes NN structure.**

| Retrieval | Scheme       | Inputs | Hidden nodes | Outputs |
|-----------|--------------|--------|--------------|---------|
| Temperature | scheme 1     | 15     | 30           | 51      |
|           | scheme 2     | 24     | 30           | 51      |
|           | scheme 3     | 24     | 30           | 51      |
|           | scheme 4     | 24     | 30           | 51      |
| Humidity  | scheme 1     | 20     | 15           | 51      |
|           | scheme 2     | 33     | 30           | 51      |
|           | scheme 3     | 33     | 30           | 51      |
|           | scheme 4     | 33     | 30           | 51      |

The flowchart figure of retrieval scheme is illustrated in Figure 4. The retrieval is divided into three steps. First, based on the AMSU-A and MHS radiances, NN (scheme 1) is used to retrieve the initial temperature and humidity profiles and the near-surface temperature and humidity. Second, the initial retrievals and the AMSU-A and MHS radiances are used to calculate the radiations of equation (6). Finally, the AMSU-A and MHS radiances and the radiations of equation (6) are used as NN (schemes 2/3/4) inputs to retrieve the temperature and humidity profiles.
Figure 4. The flowchart figure of retrieval scheme.

4 Simulation experiment

4.1 Radiation ratio

For the lower atmosphere microwave channels, the ratio of the surface emissivity item \( \frac{\varepsilon I_s}{I} \) to the sensor measurement radiation \( I \) is large, and the ratio of the other items to \( I \) is small; thus, the change in \( I \) caused by the temperature and humidity profiles is small, which is disadvantageous for temperature and humidity profiles retrieval. Therefore, reducing the ratio of the surface emissivity item is beneficial to temperature and humidity profiles retrieval.

In equations (1) and (6), the ratio of the surface emissivity item is

\[
D = \frac{\varepsilon I_s}{I} \times 100\%
\]

\[
D_\delta = \frac{\delta \varepsilon I_{s I}}{I} \times 100\%
\]

To study the influence of different surface emissivity values, 6790 group normally distributed surface emissivity values with a mean value of 0.9 and a standard deviation of 0.02 are used as inputs of the RTTOV to calculate \( D \) and \( D_\delta \), and there are no correlation between the surface emissivity of each channel. The input profile is a 51-level reference profile of RTTOV.

Figures 5-8 show the ratio of the corresponding channel in AMSU-A, MHS, Tables 2 and 3. Comparing the channels with the weight function peaks at the same height in Figures 1 and 3, \( D_\delta \) is significantly smaller than \( D \) for the surface emissivity with a mean value of 0.9. In addition, \( D_\delta \) is significantly smaller than \( D \) for the same surface emissivity deviation. Thus, the double channel differences equation (6) can reduce the ratio of the surface emissivity item and then increase the ratio of temperature and humidity information item, which makes equation (6) more sensitive for the radiation change caused by the temperature and humidity profiles and more beneficial to the temperature and humidity profiles retrieval.
Figure 5. The ratio of AMSU-A channels, where the legend is the corresponding channel number.

Figure 6. The ratio of MHS channels, where the legend is the corresponding channel number.
4.2 Simulation retrieval experiment

The profiles in 60L-SD choose database are used as RTTOV 10.2 inputs. The corresponding surface emissivity values are same as section 4.1. The scan angles are set to 0°. Noise equivalent temperature sensitivity (NEDT) is applied to each channel radiation of AMSU-A and MHS. During retrieval, the first 5000 profiles are trained in the NN, and the remaining 1790 profiles are used for retrieval verification.

In Figures 9 and 10, the overall root mean square error (RMSE) of scheme 2 is smaller than that of scheme 1 both without and with NEDT, and the bias of scheme 2 is basically the same as that of scheme 1 both without and with NEDT. For temperature retrieval, the RMSE of scheme 2 is significantly reduced below 600hPa, and the maximum RMSE reductions are 0.55K and 0.35K without and with NEDT, respectively. For relative
humidity retrieval, the RMSE of scheme 2 is significantly reduced below 500hPa, and the maximum RMSE reductions are 4.3% and 5.3% without and with NEDT, respectively.

**Figure 9.** Temperature RMSE and bias profiles without and with NEDT.

**Figure 10.** Relative humidity RMSE and bias profiles without and with NEDT.

Figure 11 shows statistics of data used for retrieval in the 60L-SD choose database. Figures 12 and 13 show statistics of retrievals of scheme 1 and scheme 2 without and with NEDT, respectively. The vertical distribution of the retrieval profiles in scheme 2 is closer to the target profiles than that of scheme 1 without and with NEDT, especially for the relative humidity profiles. In addition, compared with scheme 1, scheme 2 significantly modified the
data distribution of lower atmosphere temperature and relative humidity retrievals, and could more accurately reflect the data change of the target profiles as a whole.

Figure 11. As shown in Figure 2, but statistics of data used for retrieval in the 60L-SD choose database.
Figure 12. As shown in Figure 2, but (a)-(d) statistics of retrievals of scheme 1 without NEDT, (e)-(h) statistics of retrievals of scheme 2 without NEDT.
5 Retrieval application experiment

To further analyze the retrieval performance of the double channel differences scheme, the AMSU-A and MHS L1B products between 1 February 2015 and 28 February 2015 are used to retrieve temperature and humidity profiles for cloudy and cloudless conditions, different surface types, different scan angles, and different initial values. This paper uses whether there are retrieval profiles in the IASI L2 products as the cloudy/cloudless flag, satellite_zenith of the AMSU-A L1B products as the scan angle flag and flag_landsea of the IASI L2 products as the land/coast/sea flag. To reduce the influence of surface altitude, only data with an altitude of less than 500 m are selected. The corresponding ERA-Interim 0.5°×0.5° reanalysis data are selected as the target profiles. After data matching and screening, a total of 6,694,539 profiles are obtained for the temperature and relative humidity retrieval. Of these data, 85% are selected for training, and 15% are used for verification. Figure 14 shows the statistics of the selected ERA-Interim database.

Figure 13. As shown in Figure 2, but (a)-(d) statistics of retrievals of scheme 1 with NEDT, (e)-(h) statistics of retrievals of scheme 2 with NEDT.
5.1 Retrieval results

Figures 15 and 16 show the temperature RMSE and bias of schemes 1 and 2 for land, coast and sea under cloudless and cloudy conditions. The RMSE of scheme 2 is obviously smaller than that of scheme 1 in the lower atmosphere, and the RMSE improvement of land is greater than those of coast and sea. In addition, the RMSE improvement has no significant dependence on the scan angle. Under the cloudless condition, the maximum RMSE improvements in the lower atmosphere for the land, coast and sea are 0.64K, 0.42K and 0.37K, respectively; under the cloudy condition, the maximum improvements in RMSE are 0.62K, 0.48K and 0.52K, respectively. Except for the land under cloudy condition, the temperature bias of scheme 2 is smaller than that of scheme 1 in the lower atmosphere.
Figure 15. Temperature RMSE and bias under the cloudless condition: (a)-(c) RMSE profiles at 0° scan angle, (d)-(f) RMSE of different scan angles at 1050 hPa, (g)-(i) bias profiles at 0° scan angle, (j)-(l) bias of different scan angles at 1050 hPa.
As shown in Figure 15, but under cloudy condition. Figures 17 and 18 show the relative humidity RMSE and bias of schemes 1 and 2 for the land, coast and sea under cloudless and cloudy conditions. The RMSE of scheme 2 is significantly smaller than that of scheme 1 from 300–1050 hPa, and the RMSE improvement of land is greater than that of coast and sea. The relative humidity RMSE profiles have the largest improvement from 600–800 hPa and the RMSE improvement has no obvious dependence on the scan angle. Under the cloudless condition, the maximum RMSE improvements at 702.7 hPa for land, coast and sea are 5.15%, 5.88%, and 3.56%,
respectively; under the cloudy condition, the maximum improvements in RMSE are 9.03%, 8.19%, and 7.32%, respectively. In summary, the double channel differences scheme can significantly reduce the RMSE of temperature profiles in the lower atmosphere and humidity profiles in the middle and lower atmosphere, and the retrieval results are basically the same as those of simulation experiment. The relative humidity bias of scheme 2 is basically the same as that of scheme 1.
**Figure 17.** Relative humidity RMSE and bias under the cloudless condition: (a)-(c) RMSE profiles at 0° scan angle, (d)-(f) RMSE of different scan angles at 702.7 hPa, (g)-(i) bias profiles at 0° scan angle, (j)-(l) bias of different scan angles at 1050 hPa.

**Figure 18.** As shown in Figure 17, but under cloudy condition.

Figure 19 shows statistics of data used for retrieval in the selected ERA-Interim database. Figure 20 shows statistics of retrievals of scheme 1 and scheme 2. For the
temperature, the vertical distribution of the retrieval profiles in scheme 2 is basically the same as that of scheme 1. However, compared with the lower atmosphere temperature distribution of the target profiles (Figure 19), scheme 2 can better describe the characteristics of temperature changes in different intervals. For relative humidity, scheme 2 improves the vertical distribution of the retrieval profiles, and reduces the number of profiles in the lower atmosphere relative humidity distribution large value area, thereby closer to the target profiles.

**Figure 19.** As shown in Figure 2, but statistics of data used for retrieval in the selected ERA-Interim database.
Figure 20. As shown in Figure 2, but (a)-(d) statistics of retrievals of scheme 1, (e)-(h) statistics of retrievals of scheme 2.

5.2 Influence of initial value

Figures 21 and 22 show the temperature RMSE and bias of schemes 2, 3 and 4 for land, coast and sea under cloudless and cloudy conditions, respectively. Compared to scheme
scheme 3 has a significantly reduced RMSE (below 900 hPa), and the RMSE improvement has no significant dependence on scan angle. Under the cloudless condition, the maximum RMSE improvements in the lower atmosphere for land, coast and sea are 3.25K, 2.2K and 1.56K, respectively; under the cloudy condition, the maximum RMSE improvements are 3.03K, 2.12K and 1.94K, respectively. Thus, the initial near-surface temperature has a very important influence on the double channel differences scheme regarding the reduction RMSE in the lower atmosphere. The temperature bias of scheme 3 is smaller than that of scheme 2 in the lower atmosphere, especially for land and coast.

Compared to scheme 3, scheme 4 shows a small improvement of 0.2K from 600–900 hPa. Since the RMSE profiles of scheme 1 is the RMSE improvement of scheme 4 compared to scheme 3 and significantly greater than 0.2K, the double channel differences scheme is relatively insensitive to the initial temperature profiles. The bias of scheme 4 is basically the same as that of scheme 3.
Figure 21. As shown in Figure 15, but different schemes.
Figures 23 and 24 show the relative humidity retrieval RMSE and bias of schemes 2, 3 and 4 for land, coast and sea under cloudless and cloudy conditions, respectively. Scheme 3 can reduce the relative humidity RMSE below 900 hPa compared to scheme 2. Under the cloudless condition, the maximum RMSE improvements for land, coast and sea are 3.04%, 3.1% and 2.34%, respectively; under the cloudy condition, the maximum RMSE improvements are 3.35%, 2% and 2.01%, respectively. For the initial near-surface relative humidity of 10% RMSE improvement (Figures 14 and 15), the RMSE improvement of scheme 3 compared to scheme 2 is less than that of the initial near-surface relative humidity. In addition, compared to scheme 3, scheme 4 has a slight improvement of 1%–3% from 700–900 hPa. Compared to the initial relative humidity RMSE profiles (Figures 14 and 15), the double channel differences scheme is relatively insensitive to the initial relative humidity profiles. The bias of scheme 3 and scheme 4 are basically the same as that of scheme 2.
Figure 23. As shown in Figure 15, but for relative humidity RMSE and bias of different schemes under cloudless condition.
Figure 24. As shown in Figure 15, but for relative humidity RMSE and bias of different schemes under cloudy condition.

Figure 25 shows statistics of retrievals of scheme 3 and scheme 4. The vertical distribution of the retrieval profiles in scheme 3 is basically the same as that of scheme 4. Compared with scheme 2, scheme 3 and scheme 4 further improve the vertical distribution of the retrieval profiles and reduce the number of profiles in the large value area of the lower
atmosphere temperature and relative humidity distribution, thereby closer to the target profiles.

Figure 25. As shown in Figure 2, but (a)-(d) statistics of retrievals of scheme 3, (e)-(h) statistics of retrievals of scheme 4.
6 Summary and discussion

To reduce the dependence of temperature and relative humidity profile retrievals on surface emissivity, a double channel differences scheme is proposed in this paper. By analyzing the weight function, the channel selection and the ratio of the surface emissivity item, this paper preliminarily illustrates the feasibility of improving retrieval accuracy of the double channel differences scheme. The retrieval performance of the double channel differences scheme is simulated both with and without NEDT and further analyzed by using one month of global AMSU-A and MHS measurements. In addition, the sensitivity of the double channel differences scheme to the initial values is analyzed. The above studies show that the double channel differences scheme can reduce retrieval RMSE of temperature and relative humidity profiles.

The results are encouraging: the double channel differences scheme can significantly reduce the RMSE of temperature profiles in the lower atmosphere and humidity profiles in the middle and lower atmosphere for cloudy and cloudless conditions, different surface types, and different scan angles. The distribution of retrievals is closer to the target profiles. In addition, the RMSE improvement has no significant dependence on the scan angle. For temperature retrieval, under the cloudless condition, the maximum RMSE improvements for land, coast and sea are 0.64K, 0.42K and 0.37K, respectively; under the cloudy condition, the maximum RMSE improvements are 0.62K and 0.48K and 0.52K, respectively. For relative humidity retrieval, under the cloudless condition, the maximum RMSE improvements at 702.7 hPa for the land, coast and sea are 5.15%, 5.88% and 3.56%, respectively; under the cloudy condition, the maximum RMSE improvements are 9.03%, 8.19%, and 7.32%, respectively.

Initial temperature and humidity profiles and near-surface temperature and humidity with less error can reduce the temperature and relative humidity retrieval RMSE of double channel differences scheme. Reducing the initial near-surface temperature error has an important influence on lower atmosphere temperature retrieval; under the cloudless condition, the maximum RMSE improvements for the land, coast and sea are 3.25K, 2.2K and 1.56K, respectively; under the cloudy condition, the maximum RMSE improvements are 3.03K, 2.12K and 1.94K, respectively. Compared with the initial temperature and relative humidity profiles and the near-surface temperature and relative humidity RMSE reduction, the temperature retrieval results of the double channel differences scheme are not sensitive to the initial temperature profiles, and the relative humidity retrieval results of the double channel differences scheme are not sensitive to the initial temperature and relative humidity profiles and the near-surface temperature and relative humidity. Reducing the initial temperature and humidity profiles and near-surface temperature and humidity error can further improve the vertical distribution of the retrieval profiles and reduce the number of profiles in the large value area of the lower atmosphere temperature and relative humidity distribution, thereby closer to the target profiles.

In this paper, the double channel differences equation is constructed by using the relationship between the surface emissivity of adjacent channels. The simulation experiment results show that the scheme can significantly reduce the temperature and humidity RMSE. Further study using satellite measurements yield similar results. However, whether the scheme is consistent with the improvement for various surface types need to be investigated, and which channel combination is more beneficial to reducing the retrieval error remains a problem. Further analysis is needed to determine the characteristics of the double channel differences equation. In addition, for the neural network, the representativeness of the training profiles database will affect the retrieval results, and needs to be studied in detail in
subsequent studies. Although the double channel differences method in this paper is only used for microwave channels, it can be extended to hyperspectral infrared temperature retrieval. For satellite data assimilation, the double channel differences scheme can be considered as new constraints to improve the application of the microwave data.

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