A New Dynamic Emissivity-retrieval Scheme Based on Wavelet Atlas Constraints and Its Application into Land Surface Satellite Data Assimilation

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Abstract. Accurate description of surface information, including land surface emissivity, is a prerequisite for assimilating satellite observations over land. In this study, we used an emissivity atlas, essentially an image matrix containing noise from unknown sources, to improve the assimilation of observational data. First, we proposed a wavelet method for advanced image processing to denoise the emissivity atlas and developed a wavelet emissivity atlas suitable for the temperature sounder onboard the Chinese FY-3C satellite. Second, based on a real-time pixel dynamic emissivity retrieval scheme and using the wavelet atlas as the constraint set, we constrained dynamic retrieval emissivity values to eliminate retrieval errors. Finally, we designed and optimized a new assimilation system that can successfully utilize low-level microwave sounding channels of the FY-3C satellite. The results showed that the first-guess departures of the middle- and low-level channels were significantly improved as a result of the improved surface emissivity values. Compared with the emissivity atlas scheme, over-land observational data of the middle- and low-level channels could be increased by approximately 4–8%. Moreover, the addition of a large amount of new observational data did not negatively affect the analysis fields but rather improved short-term prediction results.

1. Introduction
In microwave remote sensing, low-level channel observations from low satellites can provide abundant atmospheric data with more weather information. A breakthrough in resolving the assimilation problem of such data and further exploration of assimilation capacity will enhance the contribution of microwave satellite observations to the improvement of numerical weather prediction.

Low-level sounding channel data cannot be used directly because of uncertainties in land surface emissivity. As pointed out by McNally, correction bias, emissivity modification, and cloud and precipitation detection should be considered during the data assimilation process[1]. Therefore, the premise of low-level channel data assimilation is to separate surface and atmospheric effects to improve the calculation accuracy of complex surface emissivity[2]. Although it is difficult to obtain all global microwave surface emissivity types, some of them can be calculated from the established emissivity models. However, such emissivity models are often established under limited regional surface conditions, thus preventing their use in large-scale applications[3][4]. Another method
involves direct emissivity estimation based on satellite data. Satellite observations are subject to fewer influencing factors and the observational region can be extended globally. In addition, combined multi-band and multi-sensor observations can be taken simultaneously. Krzeminski et al. of the European Center for Medium-Range Weather Forecasts (ECMWF) and Karbou et al. of the French Meteorological Bureau used a more direct and dynamic approach, obtaining surface emissivity through clear-sky microwave window channel retrieval. Weng et al. established a land surface emissivity model that effectively improved the accuracy of surface emissivity calculations for complex land surface types, especially ice, snow, and desert land, thus improving numerical weather prediction results.

Lu Qifeng performed a quantitative evaluation of the quality and prospective applications of FY-3A satellite data based on the ECMWF Numerical Weather Prediction (NWP) platform, which laid a foundation for applications of FY-3A radiance data. On the basis of Lu Qifeng's work, Chen Keyi et al. used the ECMWF assimilation system to test observations of the FY-3A/B MicroWave Humidity Sounder (MWHS), and demonstrated the positive effect of MWHS observations on numerical prediction results of the ECMWF system. Dong Peiming et al. expanded the assimilation function of the Weather Research and Forecasting Data Assimilation (WRFDA) system to include the FY-3A/B microwave observations.

2. Wavelet atlas

2.1 NGWT wavelet threshold denoising algorithm

Wavelet denoising is premised on the transformation of original signals into the wavelet domain using various wavelet bases. In the wavelet domain, the signal energy is mainly distributed into low-resolution scaling coefficients and some large wavelet coefficients, while the noise energy is evenly distributed into low-resolution scaling coefficients and all wavelet coefficients. Therefore, the wavelet threshold denoising method involves the retention of large wavelet coefficients, while rejecting small ones. The advantages of this denoising method lie in its robustness, ease of calculation, and requirement of only a small amount of prior signal information. In this section, we introduce the non-linear non-Gaussian wavelet threshold (NGWT) denoising method with spatial localization that can be used for eliminating random noise during surface emissivity retrieval. This method was proposed by Huang Qunbo and Liu Bainian. First, an iterative algorithm was used to obtain the threshold based on the wavelet signal characteristics. Subsequently, considering the spatial correlation of the signal, we designed an improved auto-correcting threshold algorithm that can reduce residual errors caused by excessive noise on some of the scales. In this manner, the noise content on each scale can be decreased and the filtering effect can be improved.

2.2 Wavelet atlas design and implementation

First, we selected clear-sky FY-3C MWTS-II observations collected in July 2014 and calculated the surface emissivity range offline as (55.3E, 124.7E) and (8.5S, 44.2N). The NCEP reanalysis data were used as the first-guess value field of the temperature and humidity profiles. Brightness temperature was simulated on the basis of the fast radiative transfer model (RTTOV) using the official CNRM Atlas featured in the RTTOV as a reference (for simplification hereinafter referred to as the CNRM atlas). The atlas has proven to be relatively stable with respect to the monthly mean AMSU emissivity curves based on scanning locations and land surface types, and its standard deviation for the daily emissivity variation of all channels is less than 0.02. Due to surface emissivity variations over time and different overpass times of polar-orbiting satellites, a wavelet emissivity atlas was developed on the basis of the assimilation system. Figures 1, 2, and 3 show the estimated off-line emissivity calculated according to satellite observations, the CNRM Emissivity Atlas, and the Wavelet Emissivity Atlas, respectively. The main characteristics of Figures 1 and 2 are similar in the shown region, with the desert, water bodies, and other geographic features being well represented. However, deviations in detail are extremely large. These deviations inevitably include the effect of unknown
noise. In addition, because the emissivity atlas was essentially a matrix image, the deviation information of both figures was denoised using the image wavelet denoising, and the dynamic equilibrium between the two was analyzed to reduce the effect of noise and improve the accuracy of the emissivity atlas. The wavelet atlas in Figure 3 can not only reflect geographic variations of emissivity over space in clear detail but also prevents excessive blurriness and noise, which are evident in the first two types of emissivity images. In order to quantify the deviations between the offline calculated emissivity atlas and the wavelet emissivity atlas with respect to the CNRM Emissivity Atlas, we calculated their RMSE as 0.0618 and 0.0545, respectively, indicating that statistical errors of the wavelet atlas are smaller.

![Fig. 1. The estimated off-line emissivity based on FY-3C MWTS-II observations in July, 2014](image1)

![Fig. 2. The CNRM emissivity atlas in July, 2014](image2)

![Fig. 3. The wavelet emissivity atlas in July, 2014](image3)
3. Dynamic emissivity retrieval scheme

3.1 Principles of surface emissivity retrieval based on satellite observations
For a non-scattering plane-parallel atmosphere, satellite microwave brightness temperature observations can be expressed as [14]:

\[ T_b = e^{\tau} T_s + T_u + (1-e) T_d \Gamma \]

(1)

where \( T_b \) is brightness temperature, \( e \) is surface emissivity, \( T_s \) is surface temperature, \( \Gamma \) is atmospheric transmittance, which is related to the optical depth \( \tau \), \( H \) is the top-of-atmosphere altitude, \( T_u \) and \( T_d \) respectively represent upwelling and downwelling brightness temperatures, \( \mu \) is the cosine of the incident zenith angle. To obtain atmospheric upwelling and downwelling brightness temperatures, the short-term temperature and humidity forecast profiles were input into the fast radiative transfer model RTTOV to calculate the amount of radiation contributed by each atmospheric layer. Under clear-sky, high-altitude, and non-precipitation conditions, the atmospheric transmittance of the window channel was close to 1, and thus, the upwelling and downwelling brightness temperatures were low, indicating that satellite microwave observations are strongly influenced by surface emissivity. Given the fixed detection path of the apparatus and the channel frequency, emissivity can be obtained using the following retrieval formula:

\[ e = \frac{T_u - T_d \Gamma}{(T_s - T_d \Gamma)} \]

(2)

Evidently, emissivity is a function of the satellite observation brightness temperature, surface temperature, atmospheric upwelling and downwelling brightness temperatures, and stratified atmospheric transmittance.

3.2 Wavelet atlas constraint scheme
The advantage of the dynamic surface emissivity retrieval scheme is that it can provide the most recent emissivity value and match it to the corresponding observation points. However, it excessively depends on real-time atmospheric conditions and sounding channel characteristics. When atmospheric transmittance decreases due to changing conditions, such as a change in cloud water content, satellite radiance is affected significantly, and the retrieval results may contain unpredictable errors. Therefore, in order to refine the dynamic emissivity retrieval scheme, the following constraint is placed on the real-time surface emissivity value:

\[ |e_{dy} - e_{at}| < \sigma \]

(3)

where, \( e_{dy} \) is the real-time dynamically retrieved surface emissivity value that can be obtained using Equation (2), and \( e_{at} \) is the surface emissivity constraint value; better results can be obtained with a more precise constraint set. In this study, the wavelet atlas was used as the constraint set. When the difference between the dynamically retrieved surface emissivity and the constraint set is smaller than the specified threshold \( \sigma \), the obtained emissivity value is considered reliable and can be used in the assimilation system to perform simulations. Otherwise, the constraint value is extracted and used as the surface emissivity value for the next simulation calculation. Based on the statistical results, the threshold \( \sigma \) is set to 0.2 on land surface.

4. ASSIMILATION SYSTEM DESIGN AND TESTING
Low-level channels are considered more sensitive to land surface conditions. In this study, we considered the height distribution of the MWTS-II peak weighting function and results of previous numerical studies in China and abroad and used the AMSU-A instrument as a reference. We determined the weighted peak height of the MWTS-II channel 4 to be the demarcation line, such that
channels with weighted peak values less than that of channel 4 (around 700 hPa) are categorized as low-level channels.

4.1 Assimilation system process

In this study, the range of the assimilation system region was set at (55.3E, 124.7E) and (8.5S, 44.2N), and a six-hour assimilation window was selected. The start time was July 22, 2014 at 06:00 (unless otherwise noted, all time references in this paper are in Coordinated Universal Time, UTC), and three-hour data before and after the start time was entered in the assimilation window. The WRF model had 36 vertical levels, with a horizontal resolution of 36 km. The assimilation data included conventional observations (surface stations, buoys, high altitude detection, wind profiler radar) and non-conventional satellite observations (such as AMSU-A and MWTS-II data). The background field at the start time was generated from the NCEP FNL global reanalysis data through a six-hour forecast of the WRF model, and four analysis fields were obtained every day at 00:00, 06:00, 12:00, and 18:00. The experiment was performed with a cyclic assimilation-forecast approach involving a three-dimensional variational assimilation carried out every six hours. The assimilation system improved the analysis field by continuously absorbing the latest observational data. On this basis, a 72-h short-term forecast was performed, and the background field required for the next assimilation was generated simultaneously. To determine the effect of surface-sensitive low-level channels of the FY-3C microwave temperature sounder on the forecasting results of a complex assimilation system, we designed several experimental groups (Table 1).

Table 1. The design of five experiment groups.

| Group name               | Method            | Obs.     | Chan. | Surface |
|--------------------------|-------------------|----------|-------|---------|
| Exp_dyn_ch48_mwts2       | Dynamic<sup>1</sup> | MWTS-II  | 4-8   | LandSea |
| Exp_dyn_ch58_mwts2       | Dynamic           | MWTS-II  | 5-8   | LandSea |
| Exp_wave_ch48_mwts2      | Wavelet atlas     | MWTS-II  | 4-8   | LandSea |
| Exp_wave_ch58_mwts2      | Wavelet atlas     | MWTS-II  | 5-8   | LandSea |
| Exp_sea_ch58_mwts2       | Fastem5<sup>2</sup> | MWTS-II  | 5-8   | Sea     |
| Exp_dyn_ch59 AMSU-A      | Dynamic           | AMSU-A   | 5-9   | LandSea |
| Exp_sea_ch69 AMSU-A      | Fastem5           | AMSU-A   | 6-9   | Sea     |

<sup>1</sup> Dynamic: Dynamic emissivity retrieval scheme constrained by wavelet atlas constraint.

<sup>2</sup> FASTEM5: A sea surface emissivity model in RTTOV.

4.2 Assimilation forecasting experiment

4.2.1 Data quantity change

Figure 4(a) shows changes in the total amount of observational data (sea + land) of each experimental group processed by the assimilation system, with the Exp_sea_ch58 mwts2 group only assimilating MWTS-II sea surface data. Figure 4(b) shows the respective relative rates of increase of observational data from each channel of three experimental groups, namely, Exp_dyn_ch48 mwts2, Exp_dyn_ch58 mwts2, and Exp_wave_ch48 mwts2 with respect to the Exp_wave_ch58 mwts2 experimental group (test baseline). That is, rate of increase<sub>i</sub> = test<sub>i</sub>-baseline<sub>i</sub>/baseline<sub>i</sub>, where <i>i</i> is the channel index.
Compared with the static atlas scheme, the dynamic retrieval experiment could absorb more observational data. Furthermore, the addition of low-layer channel 4 increased the amount of assimilated data of other high-peak channels. The introduction of the dynamic retrieval scheme and the addition of low-level channel 4 enabled significant increase of observational data of channels 5–7 by approximately 4–8%, whereas the increase was relatively small for higher-level channel 8 because it had the highest peak-value, which made it less surface-sensitive.

4.2.2 Brightness temperature simulation analysis

Figure 5 shows the statistical distribution of first-guess departures during the period from 6:00 on July 15, 2014 to 6:00 on July 31, 2014. The statistical results of both emissivity retrieval schemes were good, particularly those of the dynamic emissivity-retrieval. The statistical characteristics of the first-guess departures were significantly improved in the dynamic retrieval scheme experiment, particularly for window channel 1 with the average value approaching 0. After entering low-level channel 4 into the assimilation system, the highest expected distribution value was -2.59 for the dynamic retrieval scheme, whereas it was short of -3.07 for the atlas scheme, clearly showing improved distributional characteristics of the first-guess departures. Nevertheless, the results varied for different channels. As the peak-value of a channel increased, its surface-sensitivity decreased, thus resulting in an improvement of the simulation results. For example, channel 6, which is not very surface-sensitive, did not show much improvement. Similar results were obtained for sea surface, which indirectly proved the reliability of the dynamic retrieval scheme. It is evident from the sample number distribution of the sampling histograms that the first-guess departures and variations were significantly reduced, allowing more usable observational data into the assimilation system. In addition, simulations of sea surface observations were not greatly affected by the emissivity schemes (Figure 5b, d, f, and h).
Fig. 5. The histogram of first guess departure before bias correction in the experiment groups Exp_dyn_ch48_mwts2 (blue line) and Exp_wave_ch48_mwts2 (red line), where the left column is the land surface, the right column is the sea surface, from top to bottom are the channel 1 (a and b), the channel 4 (c and d), the channel 5 (e and f).

4.2.3 Analytical field quality

Figure 6 shows a comparison between the analysis departures of 850-hPa temperature fields obtained from four assimilation group experiments (a-d) at 6:00 on July 22, 2014. In general, the average 850-hPa pressure level are significantly affected by the surface type at about 1500 m. The following conclusions can be drawn:

1) Comparing Figures (a)-(c) with Figure (b), the temperature field distribution of Figure (a), which includes the surface-sensitive low-level MWTS-II channel 4, is significantly closer to the actual field observations, even though both figures represent the dynamic emissivity retrieval scheme. In addition, although Figure (c) is based on the wavelet atlas scheme, adding the low-level channel 4 also improved the temperature field distribution, clearly indicating that the addition of MWTS-II low-level channel information positively affects the assimilation of the low-level atmospheric temperature field.

2) The temperature distribution characteristics in Figure (d), which only assimilated the sea surface MWTS-II channels 5-8, were significantly worse for both normal and extreme temperatures.

In addition, the 850-hPa humidity analysis departure fields obtained in the four assimilation experimental groups were similar to the temperature fields (the corresponding figures are not shown to maintain the length of the paper).

As previously mentioned, more microwave observations will contribute towards the acquisition of atmospheric temperature and humidity fields. For most surfaces, the assimilation effect was maintained even after the addition of surface-sensitive channels, and the acquisition of analysis fields as well as the accuracy of initial atmospheric conditions for forecasting models were improved.
4.2.4 Forecast-influencing factors

We analyzed the impact of the analysis fields, which were improved by the surface-sensitive channels, on the forecasting results. Figure 7 shows 72-h forecasting errors of the 500 hPa geopotential height with Exp_wave_ch58_mwts2 as the experiment baseline. The addition of the dynamic retrieval scheme (green line), or the low-level channel (blue line), or the simultaneous addition of both (red line) all had obvious positive effects on 500 hPa geopotential height errors. Combinations of low-level channel 4 with the dynamic retrieval scheme and the wavelet atlas provided similar forecasting results, but the static atlas obviously contributed to the dynamic retrieval scheme. The evaluation scores of both schemes clearly exceeded the score of the experimental group Exp_dyn_ch58_mwts2, in which low-level channel 4 was not included. This shows the important contribution of low-level channel 4 to the improvement of the forecasting score.

5. Summary

The addition of low-level channels into the assimilation system could not only increase the amount of observational data of low-level surface-sensitive channels and provide more low-level atmospheric weather information but also affect middle and high-level channels by increasing the amount of observations that can be assimilated from these channels.

The assimilation experiment results showed that the current quality control program could prevent the analysis fields from being severely affected by errors. Low-level surface-sensitive channels could
improve temperature and humidity fields by providing additional information on atmospheric
temperature and humidity, thus enhancing regional forecasting accuracy. However, it should be noted
that the dynamic retrieval scheme has some shortcomings and its basic theory and operation require
further improvements, such as providing more detailed specification of errors due to surface properties,
modifying the assumption that the Earth surface is a flat mirror reflector, refining sea ice and snow cap
coefficients, and adding the retrieval of surface temperature and other variables.

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