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A PRELIMINARY STUDY ON THE 3DVAR ASSIMILATION OF THE AMSU-A DATA IN SPACE-TIME MULTISCALE ANALYSIS SYSTEM

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Abstract: Assimilating satellite radiances into Numerical Weather Prediction (NWP) models has become an important approach to increase the accuracy of numerical weather forecasting. In this study, the assimilation technique scheme was employed in NOAA's STMAS (Space-Time Multiscale Analysis System) to assimilate AMSU-A radiances data. Channel selection sensitivity experiments were conducted on assimilated satellite data in the first place. Then, real case analysis of AMSU-A data assimilation was performed. The analysis results showed that, following assimilating of AMSU-A channels 5-11 in STMAS, the objective function quickly converged, and the channel vertical response was consistent with the AMSU-A weighting function distribution, which suggests that the channels can be used in the assimilation of satellite data in STMAS. With the case of the Typhoon Morakot in Taiwan Island in August 2009 as an example, experiments on assimilated and unassimilated AMSU-A radiances data were designed to analyze the impact of the assimilation of satellite data on STMAS. The results demonstrated that assimilation of AMSU-A data provided more accurate prediction of the precipitation region and intensity, and especially, it improved the 0-6h precipitation forecast significantly.

Key words: multigrid; 3DVAR; space-time multiscale analysis system; numerical experiments

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1 INTRODUCTION

Short-term forecasting and nowcasting of severe convection weather using Numerical Weather Forecasting Model has been popular in the research and development of models over the past few years. The reliability of the prediction of NWP model depends not only on the model's ability but also to a great extent on the accuracy of the initial fields of the forecast model (Gao and Chou [1]; Ding et al. [2]). Therefore, how to construct initial fields of more accuracy and higher resolution using more observation data, especially non-conventional observation data, has become an important research topic. The progress in meteorological satellites has greatly improved their three-dimensional detectability to the earth's atmosphere, and thus provided more valid observation information for the temporal-spatial changes of typhoon-and-storm weather systems. Over the recent years, many methods of assimilating satellite data into the NWP model have been proposed and improved (Xue [3]; Zhu et al. [4]; Li et al. [5]; Dong et al.[6]).

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In the 1980s, the Earth System Research Laboratory (ESRL), affiliated to the National Oceanic and Atmospheric Administration (NOAA) of the United States, was the first to have developed the Local Analysis and Prediction System (LAPS). LAPS is an integrated system to ingest and analyze meteorological data from different observational sources. It can combine and harmonise the input data (such as data from meteorological ground observation networks, radars, satellites, sounding detectors, airplanes, etc.) for the derivation of surface and 3D fields of temperature, geopotential height or pressure, humidity, wind and cloud with high resolution. Such 3D data is used as the initial field of NWP models to hotstart the model to improve the accuracy of the 0-6h weather forecasting (Gunter et al.[7]).

Many research works proved that LAPS is capable of rapidly combining multisource data with background fields provided by NWP model, and more effective in improving the cloud and precipitation forecasting than non-LAPS coldstart (Shaw et al. [8, 9]; Jian et al. [10]; Alberoni et al. [11]; Cui et al. [12]). However, successive correction and objective analyses methods are applied to most analyses in LAPS except that the 1DVAR assimilation method was used in humidity analysis.

After balance processing, the analyzed meteorological fields were applied to short-term and nowcasting as initial fields of the NWP model.

With the development of science and technology, especially the improvement of the computation ability of computers, NOAA ESRL started to develop high temporal-spatial resolution and multiscale data assimilation system-STMAS (Space-Time Multiscale Analysis System) which employed the multigrid variation assimilation technique developed by Xie et al. (Xie et al.[13, 14]). This system inherited part of the data quality control and analysis function of the LAPS system. Currently, this system is used in conjunction with the LAPS system. It is expected that the STMAS system will completely replace the LAPS system in the near future. The STMAS has finished assimilating conventional observation data and radar data, which has achieved preliminary effects in applications (Liu et al.[15]).

In collaboration with Xie et al., we developed modules for the assimilation of AMSU-A (Advanced Microwave Sounding Unit-A) satellite data in STMAS. In this paper, we first described the STMAS system, AMSU-A data and data bias correction, followed by introduction of a technical scheme of the assimilation of AMSU-A satellite data in the STMAS data assimilation system. Section 4 introduces the channel selection experiments of satellite data channels in STMAS. Specific to the rainstorm in Taiwan Island caused by Typhoon Morakot in August 2009, we designed comparison experiments to analyze the impact of AMSU-A data on the forecasting of precipitation in Taiwan Island, and the results of which are exhibited in section 5. Conclusion and discussion are given in section 6.

2 INTRODUCTION OF MODELS AND DATA

2.1 *STMAS (Space and Time Multiscale Analysis System)*

3DVAR or 4DVAR analysis heavily depends upon an accurate model background covariance, which is practically impossible to obtain due to the time, space and flow dependence of the covariance. To improve the analysis, a multigrid technique has been introduced by Xie et al.[13] to divide data assimilation procedure into two steps: information retrieval and statistical analysis. In the multi-grid 3DVAR, long-wave information can be obtained by minimizing the cost function over a coarse grid from the observation system, and shortwave information over a relatively fine grid. The long- and short-wave length information can be extracted in turn. This extraction of resolvable information from the observation system does not require accurate covariance. After this retrieval, it becomes a standard 3DVAR or even 4DVAR but the covariance is only needed for the residual short waves as longer waves have been retrieved in the first step. The STMAS uses a multigrid 3DVAR data assimilation scheme, and is being developed toward a new generation data assimilation system of NOAA.

The objective function of the multigrid 3DVAR for any given grid level of STMAS used in the retrieval process takes the following form:

$$J=\frac{1}{2}X^{nT}X^{n}+\frac{1}{2}\left(H^{n}X^{n}-y^{n}\right)^{T}O^{n^{-1}}\left(H^{n}X^{n}-y^{n}\right)$$

of which, n=1, 2, 3, ……, N, representing different levels of STMAS (n represents nth level grid); X is the analysis increment vector; Y is the observation innovation vector; O is the covariance matrix of observation errors; H is the observation operator; T and −1 represent matrix transition and reverse, respectively.

The domain to be analyzed is divided into multi-grids of different resolution in STMAS, and the analysis scale is controlled by the number of grids. Only the waves with limited scales can be analyzed. Therefore, STMAS starts its analysis at coarse grids. On coarse grid scale, larger-scale weather system information is first retrieved, and the analysis result of which is taken as the initial condition for the analysis at the next grid level. As the density of the grids increases, the observation information at different scales was gradually revealed.

2.2 *AMSU-A radiances data*

The satellite data used in this study is the radiances data from the AMSU-A (Advanced Microwave Sounding Unit A) onboard the NOAA-18, the third generation meteorological satellite. AMSU-A, capable of receiving microwave radiances from the atmosphere which can penetrate the atmosphere (especially clouds) within a certain depth, is mainly used to detect the atmospheric temperature. It is composed of two instruments: AMSU-A1 and AMSU-A2. AMSU-A1 has 13 microwave channels (channel 3- channel 15) with frequencies of 50.3GHz, 52.8–57.3GHz and 89.0GHz; AMSU-A2 has two channels (channel 1 and channel 2) with frequencies of 23.8GHz and 31.4GHz (Goodrum et al.[16]), nadir resolution of 48km, and scanning width of 2,226km. It allows reception of 30 radiances of different view within a scanning span of ±48.33°.

The atmospheric temperature at different altitudes can be inferred from different channels of the AMSU-A. The maximum energy contribution height of Channels 1, 2, 3, and 15 is land surface, which suggests that the information they collect is more about land surface than about any other levels; Channels 4–14 are mainly used for detecting the temperature of the atmosphere.

2.3 *Bias correction of AMSU-A satellite data*

Bias correction is a key step prior to the assimilation analysis of observation data. It eliminates the observation data that is not qualified for assimilation, and thus ensures the quality for rapid convergence in the assimilation computation and for the analysis results. A single observation data with an error or deviation would result in a significant decline in the quality of analysis and forecast results. Preliminary bias correction was performed on the AMSU-A satellite data in our study, which consisted of the following steps:1) Eliminating the data that is out of the model domain; 2) Eliminating duplicated or incomplete temporal-spatial data, and making sure the upper-level profile is continuous vertically; 3) Checking radiances of different satellite channels, and eliminating extreme satellite observations.

3 TECHNIQUE OF ASSIMILATING AMSU-A RADIANCES DATA IN STMAS

The concept of the multigrid 3DVAR implementation of STMAS was introduced by Xie et al.[13] and Li et al.[17, 18]). Below is the basic scheme for the AMSU-A radiances assimilation.

$$J=\frac{1}{2}\left(H^n(T,q)-y^n\right)^T O^{n^{-1}}\left(H^n(T,q)-y^n\right)$$

of which, H is the observation operator (also called forward operator or forward model) which simulates the observation, and is also a nonlinear function which transforms observable quantities from model prognostic variables; Y is the observed satellite radiances; n represents the nth grid; T and q represent the temperature and humidity parameters, respectively. With respect to satellite radiance data, the observation operator is the forward transfer model.

In 3DVAR, observation data is continuously assimilated into the models by minimizing an objective function and gradient using steepest descent method, so that the model parameters are calibrated and the fundamental information of the atmosphere is obtained. In the multigrid 3DVAR, the basic idea is to iterate sequentially the variational analysis beginning at the larger scales and ending at the smallest resolvable ones.

In STMAS, we currently only use the Community Radiative Transfer Model (CRTM) developed by NOAA. CRTM is a sensor-band-based fast radiative transfer model developed at the Joint Center for Satellite Data Assimilation (JCSDA). CRTM is expected to produce significant impact on the utilization of satellite data in data assimilation (Weng et al.[19]). In this study, temperature is used as the control variable of the model and assimilation tests are performed.

Multigrid STMAS starts its analysis from the coarsest grids. When n=1, Y^1 is the deviance of the observation from the background on the grid point, and T_{n-1} is the solution or approximate solution of J_{n-1}. After solving for J_{n-1}, T_{n-1} was interpolated into the n^{th} grid, and T_n can be solved by minimizing J_n. Adding each sequence of analyses together produces the STMAS final analysis.

4 SELECTION SENSITIVITY EXPERIMENTS OF AMSU-A CHANNELS

Before ingesting AMSU-A satellite data into STMAS, an analysis was performed to examine what channels can produce positive impact on STMAS. The channel selection sensitivity experiment is composed of the following two tests:

Once the radiances of different AMSU-A channels is assimilated into STMAS, whether the data of a certain channel has proper effect on assimilation is determined by analyzing the variation of the objective function of 3DVAR as the number of iterations changes during the computing process.

After the data of the channel is assimilated into STMAS, if the objective function reaches a minimum value through multiple iteration and the gradient decreases rapidly, or in another word, the minimization process is convergent, then it is considered that the optimization of the radiances of this channel in the STMAS assimilation process is successful.

Proper responses are expected over the vertical profile in STMAS analysis interval after the data of the corresponding AMSU-A channel is assimilated. Assimilation analysis was run on the data of each of the 15 NOAA AMSU-A channels. The responses of temperature profile on different channels were checked. If the contribution level is consistent with the distribution of the AMSU-A weighting function, then the impact of the channel on temperature is considered correct.

If a channel passes both tests, then it is considered liable to be assimilated into STMAS. Based on the results of the above tests, the objective function was not convergent after AMSU-A channels 1, 2, and 15 were assimilated into STMAS using CRTM. However, it was convergent when the data of other channels was assimilated into STMAS.

In addition, the influence of the land surface on the lower channels of AMSU-A may result in inaccurate radiative transfer computation, and the channels 12-14 are not eligible because they are above the model top. Therefore, Channels 5–11 were selected to be used in the STMAS assimilation system. Fig.1 shows the results of the sensitivity experiments of channel 5. Figures of the results for other channels are not shown.

Figure 1a shows the simulated brightness temperature of AMSU-A channel 5 calculated with the CRTM forward model. Fig.1b demonstrates the simulated brightness temperature of AMSU-A channel 5 calculated with the CRTM after the cost function was minimized by multiple iterations. Fig.1c exhibits the observed brightness temperature of the AMSU-A channel 5. By comparing Fig.1b with Fig.1c, it suggests that the brightness temperature of the AMSU-A channel 5 simulated by CRTM is consistent with that of the satellite observation after Jacobian was minimized. In another word, AMSU-A channel 5 reaches complete convergence after minimization iterations with CRTM, and thus channel 5 can be used in STMAS assimilation. Moreover, after channel 5 was assimilated into STMAS, compared with the temperature profile before iteration (the green line in Fig.1d), the temperature profile after

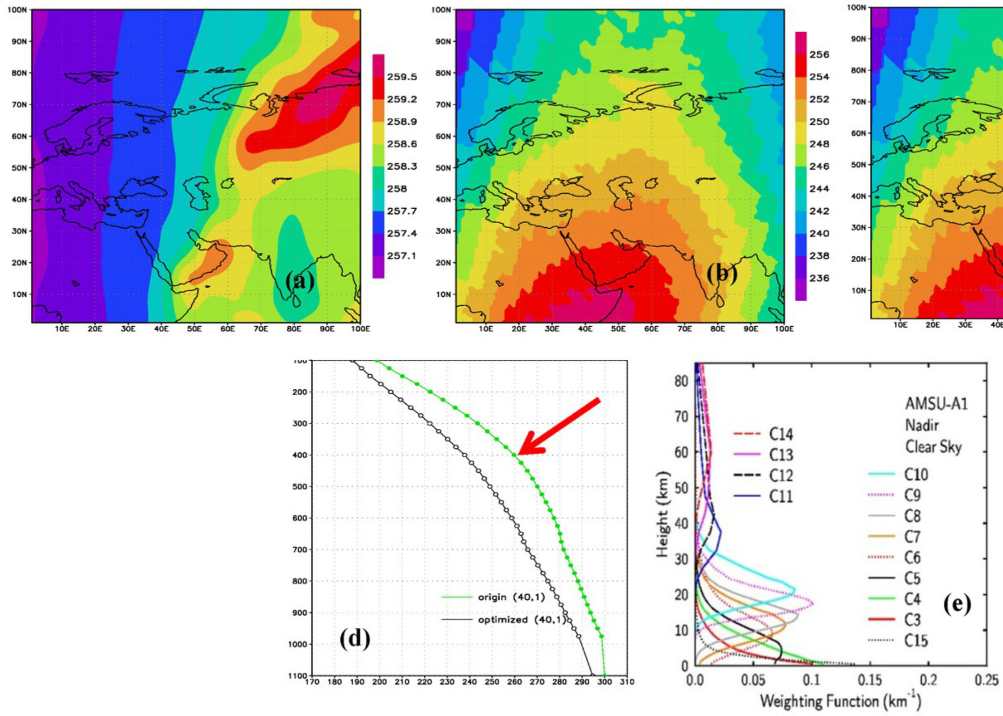

Figure 1. Results of the minimization sensitivity test on NOAA-18 AMSU-A Channel 5: (a) simulated brightness temperature of AMSU-A channel 5 calculated with the CRTM forward model; (b) simulated brightness temperature of AMSU-A channel 5 after minimization iterations with CRTM; (c) AMSU-A Observations; (d) temperature profile of one point in the domain; (e) distribution of AMSU-A weighting function.

iteration (the black line in Fig.1d) displayed the most significant change within the 500 –700hPa range. Therefore, the main impact level of the temperature profile is 500 –700hPa, which matches the position of the impact level of channel 5 in the AMSU-A weighting function (Fig.1e).

5 NUMERICAL EXPERIMENT

5.1 *Case selection*

Typhoon Morakot is one of the most devastating storms formed over the northwestern Pacific in August 2009, which severely impacted Taiwan Island. Morakot was formed around midnight on August 4, 2009. It became a medium-sized typhoon by 20:00 (UTC, same below) on August 5, and moved westwards. It hit Taiwan Island's Hualian city around 23:50 on August 7, emerged back over water from near Taoyuan at 14:00 on August 8, and entered Fujian from northern Mazu around 18:30 on August 9. Affected by Morakot, mid-south and eastern Taiwan Island had the largest rainfalls in its recorded history, which resulted in catastrophic disasters in Tainan, Gaoxiong, Pingdong, and Taidong.

The data used in this study include the AMSU-A radiances data, rain gauge observation data, radar observation data, and NCEP GFS model forecast data for August 7, 2009 provided by Taiwan Bureau of Meteorology. This test focuses on analyzing the rainfalls in Taiwan Island.

5.2 *Experiment schemes*

Two sets of experiment were designed in this paper to compare the assimilation effect of the AMSU-A radiances on STMAS. The Experiment schemes are shown in Table 1.

Table 1. Experiment schemes.

Experiments	Assimilated data of STMAS
STMAS-1	Radar Raw data, conventional data, sounding data
STMAS-2	AMSU-A Radiance data Radar Raw data conventional data, sounding data

(1) Comparison Experiment 1. The initial fields of the forecast model were provided by STMAS, where the AMSU-A radiances data is not assimilated. It is named as STMAS-1.

(2) Comparison Experiment 2. Hereafter referred to as STMAS-2, Comparison Experiment 2's only difference from Comparison Experiment 1 lies in the fact that the AMSU-A radiances data was assimilated while the initial fields were generated.

The forecast model is WRFV3.3 with a model grid of 9 km and without nesting. The two sets of experiment used the same model parameters and boundary condition, which are the forecast results of corresponding times of the NCEP GFS model. The starting forecast time is 05:00, August 7, 2009; the forecast period is 24h.

5.3 *The assimilation results of AMSU–A radiances data*

Figure 2 illustrates the temperature distribution of 100hPa, 300hPa, 500hPa, and 700hPa before and after the assimilation of the AMSU-A radiances data. It indicates the adjustment of AMSU-A data assimilation to the temperature initial field. The left chart is the temperature distribution before the assimilation of AMSU-A, and the right chart after the assimilation.

It shows that, after the assimilation of AMSU-A radiances, changes took place in each level of the temperature distribution. The temperature of each level in the waters near the south of Taiwan Island increased more or less after the assimilation, which suggests that this water area is high-temperature and high-humidity after the assimilation of the AMSU-A data, and that it is in favor of the mobility and development of typhoons.

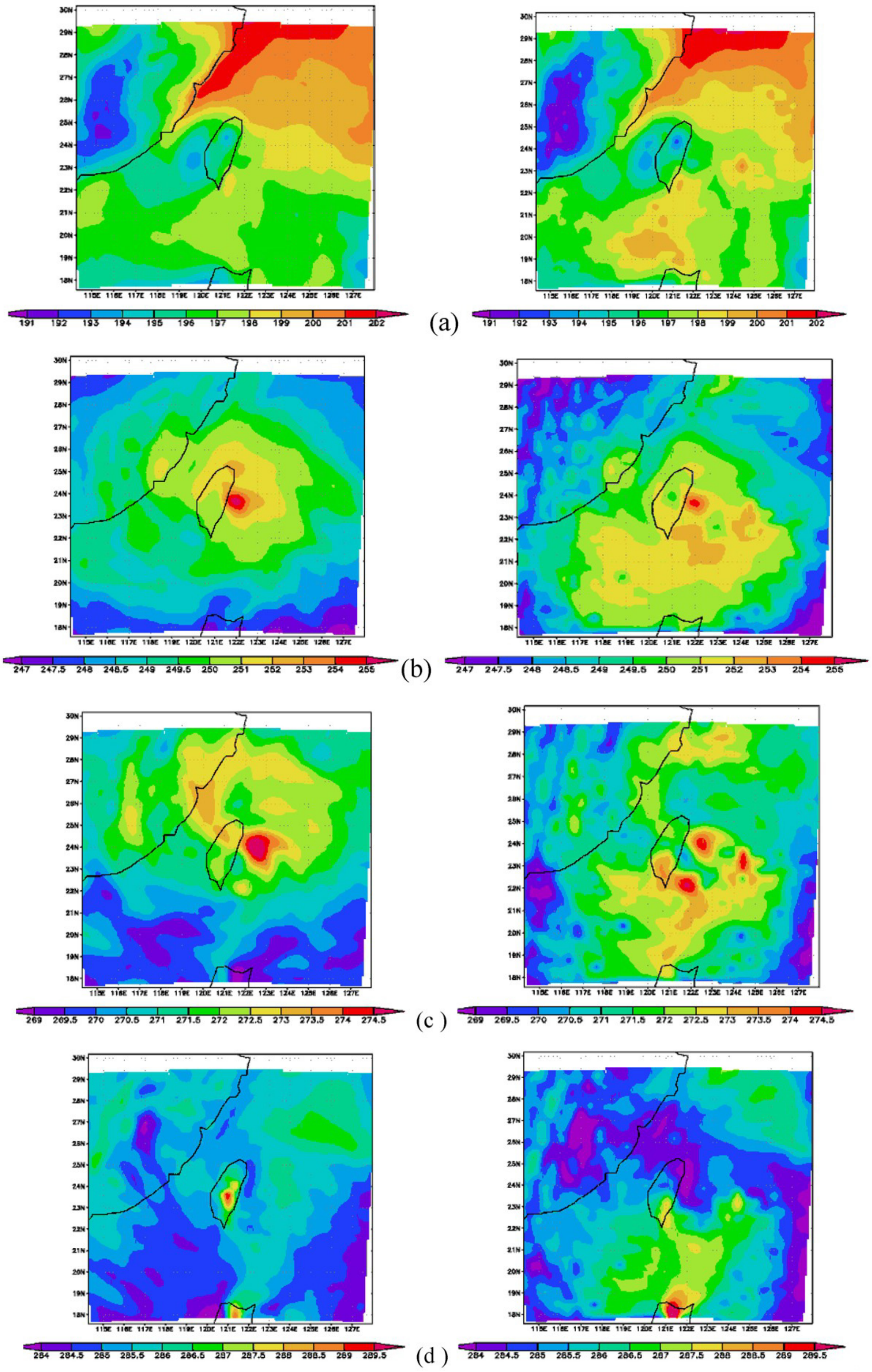

Figure 2. The impact of assimilation of satellite data on the temperature distribution at 05:00 on August 7, 2009 in the Typhoon Morakot case: (a) temperature distribution for 100hPa; (b) temperature distribution for 30hPa; (c) temperature distribution for 500hPa.; (d) temperature distribution for 700hPa. Left panels: before assimilation; right panels: after assimilation.

5.4 *Precipitation forecast results*

A comparison analysis of hour-by-hour precipitation simulated by the two sets of forecast experiment indicated that difference existed in the simulated precipitation within 1–12h between the two sets of test, and more significant difference occurred within the first 6 h. In the hours that followed, although difference still existed in the accumulated precipitation predicted by different experiment schemes, the difference was so small that it was within 2 mm even in the center of the heavy rainfall.

1h precipitation forecast by WRF and actual precipitation distribution were charted in Fig.3. Of which, Fig.3a shows the 1h forecast of precipitation by STMAS-1 where AMSU-A satellite data is not assimilated by STMAS; Fig.3b is the 1h forecast of precipitation by STMAS-2 where AMSU-A satellite data is assimilated by STMAS; Fig.3c is the radar echo distribution; and Fig.3d is the precipitation observed by ground rain gauge.

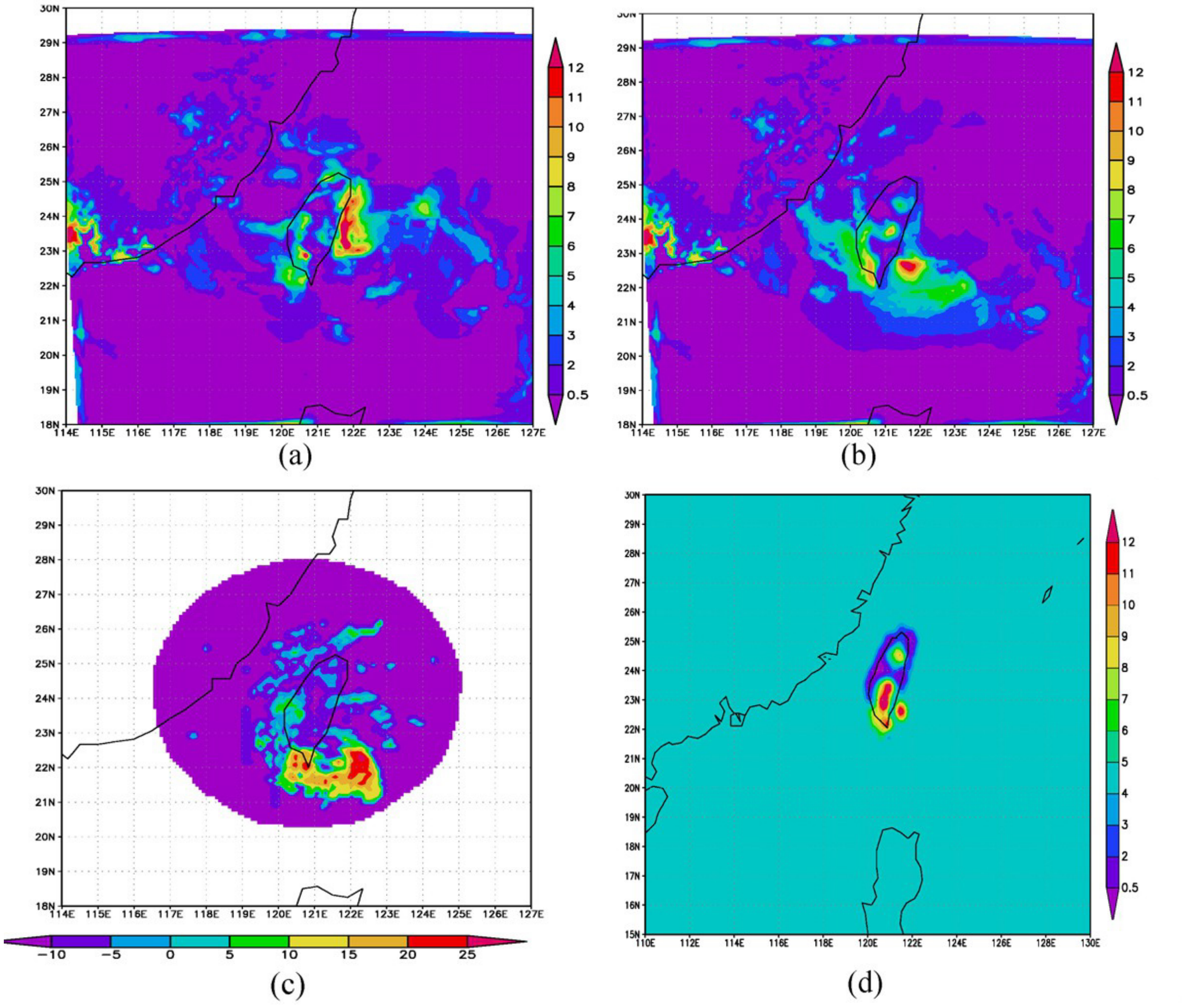

Figure 3. 1h forecast distribution of precipitation caused by Typhoon Morakot at 5:00 (UTC) on August 7, 20 (a) 1h forecast of precipitation by STMAS-1 where AMSU-A satellite data is not assimilated by STMAS; (b) 1h forecast of precipitation by STMAS-2 where AMSU-A satellite data is assimilated by STMAS; (c) Radar echo distribution; (d) Precipitation observed by ground rain gauges.

It is shown in Fig.3a that when AMSU-A data was not assimilated in STMAS, precipitation region was predicted to be mainly in a small area in the southwest of Taiwan Island and in the waters along the coastline of eastern Taiwan Island. However, after the AMSU-A data was assimilated (Fig.3b), southern Taiwan Island, especially the region along the southeastern coast, was predicted to have rainfalls with precipitation of over 12 mm, which was confirmed by both the radar echo distribution chart (Fig.3c) and the rain gauge observation (Fig.3d). Therefore, the assimilation of AMSU-A data substantially corrected the forecast of 1h precipitation region and its intensity. In addition, the rain gauge observation results demonstrated that the hourly precipitation of the high value center in northern Taiwan Island reached 8–9 mm, which was predicted in

STMAS-2 only with a lower intensity than the rain gauge observation. While the high precipitation value center forecasted by STMAS-1 was significantly off to the east.

Figure 4 shows the forecasted 2h accumulated precipitation and the actual precipitation distribution. The accumulated precipitation distribution chart for 06:00–07:00 observed by rain gauge indicates that there is a center of high precipitation value each in the south and north of Taiwan Island with precipitation of more than 21mm (Fig.4c). In southern Taiwan Island, the precipitation region and intensity of the high value center forecasted by the STMAS-2 experiment (Fig.4b) agreed with that of the actual observation (Fig.4c). It is also shown in the STMAS-2 experiment that there is a center of high precipitation value in northern Taiwan Island, where the precipitation region is consistent with the results observed by rain gauge, only with lower intensity. However, the precipitation region in southern Taiwan Island forecasted by STMAS-1 experiment (Fig.4a) is significantly smaller in size than rain gauge observation.

According to the 3-5h accumulated precipitation forecast results (figures not shown), the rainfall intensity in southern Taiwan Island forecasted by STMAS-1 is getting closer to the actual intensity, but the precipitation region is slightly off to the west. Meanwhile, the STMAS-1 forecast shows a precipitation region in northern Taiwan Island, but its intensity is lower than that observed by rain gauge. After AMSU-A data was assimilated, the location of the high precipitation center and its intensity in southern and northern Taiwan Island have become more consistent with that of the observed.

The 6h accumulated precipitation forecast (Fig.5) shows that the accumulated precipitation distributions predicted by the two experiment schemes are consistent in general. However, in the precipitation center of northern Taiwan Island, precipitation intensity is still lower than that observed by rain gauge (Fig.5c) with STMAS-1 (Fig.5a), the rainfall intensity forecasted by STMAS-2 (Fig.5b) is much closer to the actual than the STMAS-1 forecast is.

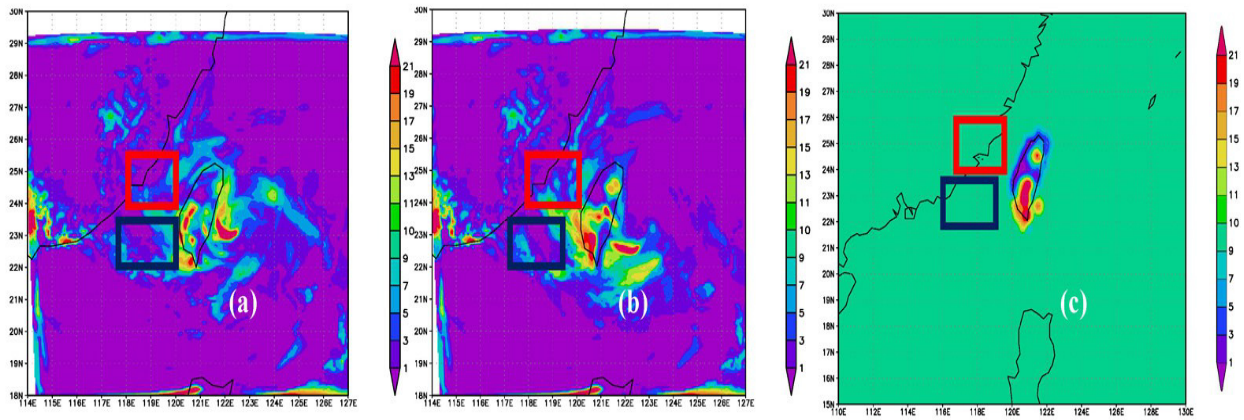

Figure 4. 6h forecast distribution of precipitation caused by Typhoon Morakot at 5:00 (UTC) on August 7, 2009. (a) 6h forecast of precipitation by STMAS-1 where AMSU-A satellite data is not assimilated by STMAS; (b) 6h forecast of precipitation by STMAS-2 where AMSU-A satellite data is assimilated by STMAS; (c) Precipitation observed by ground rain gauge.

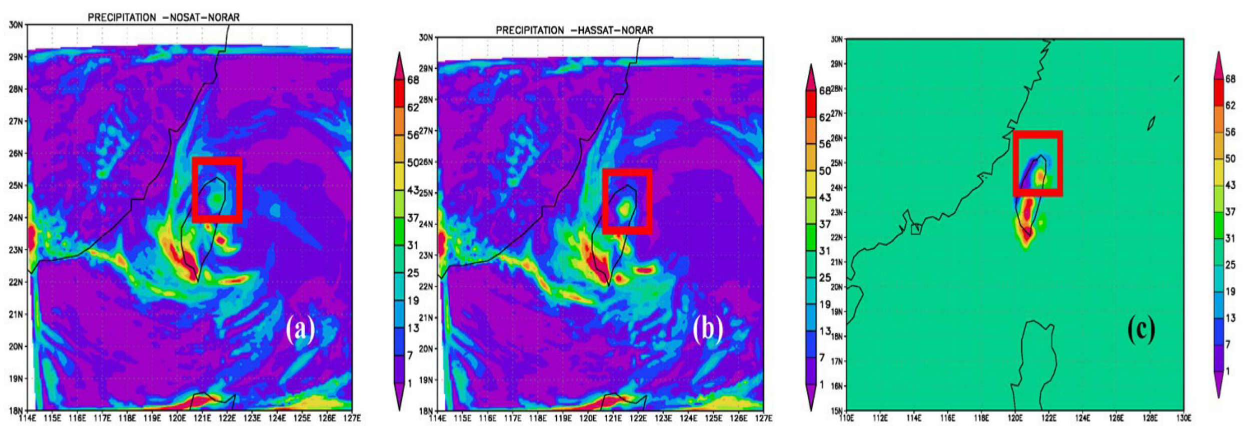

Figure 5. 6h forecast distribution of precipitation caused by Typhoon Morakot at 5:00 (UTC) on August 7, 2009. (a) 6h forecast of precipitation by STMAS-1 where AMSU-A satellite data is not assimilated by STMAS; (b) 6h forecast of precipitation by STMAS-2 where AMSU-A satellite data is assimilated by STMAS; (c) Precipitation observed by ground rain gauges.

After 7 – 24 h, the precipitation distributions forecasted by the two experiments are getting closer to each other. Therefore, in this particular case, assimilating the AMSU-A radiances data at the time of initiating the model forecast plays a positive role in forecasting the 1-6h precipitation region and intensity in Taiwan Island.

6 CONCLUSIONS AND DISCUSSION

This paper introduced the technique scheme of the assimilation of AMSU-A radiances data developed in the STMAS data assimilation system. STMAS mainly adopted the temporal-spatial multi-scale variation assimilation technique where the CTRM forward model was applied to the satellite data assimilation. The channel selection test and precipitation forecast comparison experiments have resulted in the following conclusion:

(1) The AMSU-A channel selection sensitivity test shows that after AMSU-A channels 5 – 11 were assimilated into STMAS by CRTM, the objective function was successfully minimized and converged quickly. The response levels are quite consistent with the AMSU-A weighting function, the channels of which can be used in STMAS assimilation.

(2) The scheme of assimilating AMSU-A radiances data by STMAS adjusted the initial temperature of the forecast model. In the Typhoon Morakot case, it positively affected the precipitation forecast, and thus improved the forecast accuracy of the rainfall region and intensity. Therefore, the assimilation of AMSU-A data produced a more accurate 0 – 6h precipitation forecast.

Our work in this paper speaks volumes that satellite microwave radiances data assimilation improves the initial fields of forecast models and thus improves the accuracy of precipitation forecast. It was also made obvious that the application of satellite data in data assimilation has a promising potential (Xue[3]). However, the application and development of satellite data assimilation technique in the STMAS multi-scale variational assimilation system is still in its infancy stage. In addition, our work of assimilation simulation tests was carried out on a single case.

However, during the operational trials of the model, improvement on the algorithm and technique is needed, such as preprocessing of the data observed over different surface (e.g. land, ocean) or of different type of precipitation (e.g. rainstorm, tropical cyclone), thinning of satellite data, further quality control of data, bias correction technique, assimilation of more satellite data, the reliability of the model, etc. To further verify the effectiveness of its improvement on forecast under different conditions, tests and evaluations on assimilation effect are needed before it is applied to operational platforms.

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