Research Article

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Impact of AMSU-A and MHS radiances assimilation on Typhoon Megi (2016) forecasting

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Abstract: To better understand the assimilation contribution and influence mechanism of different satellite platforms and different microwave instruments, the radiance data of Advanced Microwave Sounding Unit-A (AMSU-A) and the Microwave Humidity Sounder (MHS) onboard NOAA-15 and NOAA-18 are assimilated to investigate various assimilation effects on the prediction of path and intensity of Typhoon Megi (2016) based on Weather Research and Forecasting (WRF) three-dimensional variation and the WRF model. The community radiative transfer model is employed as the forward operator. The quality control and bias correction procedures before the radiance data assimilation (DA) are performed to improve the simulations.

Impact of AMSU-A and MHS radiances assimilation on Typhoon Megi (2016)’s path and intensity is investigated by six experiments (without and with AMSU-A and MHS DA) with initial conditions at 1200 UTC on 25 September 2016 and 60 h forecast integration.

The results are compared to the observational data from the China Meteorological Administration tropical cyclone database. The impact mechanisms of DA adjustments to the initial fields and assimilation increment analysis of each physical quantity field are investigated in detail. The findings show that NOAA-15 AMSU-A assimilation produces the best output over the course of the 60 h simulation, demonstrating that assimilation satellite data from multiple platforms is not always better than assimilation satellite data from a single platform. In comparison, MHS assimilation has a favorable effect on short-term path and strength forecasts, but has a negative impact on long-term forecasts. The effect of MHS DA needs to be further investigated.

Keywords: assimilation, Weather Research and Forecasting model’s three-dimensional variational data assimilation system, Typhoon Megi (2016), Advanced Microwave Sounding Unit-A, Microwave Humidity Sounder

1 Introduction

Tropical cyclones (TCs) often cause strong storm waves, heavy flooding, landslides, and mudslides as a result of their devastating winds and heavy rain, posing the largest danger to human life and property along the coast [1,2]. TCs that originate in the Pacific Northwest Ocean normally strike East and Southeast Asia. In comparison to inland areas, coastal areas are especially vulnerable to the impact of TCs. China is one of the countries most affected by typhoons, with coasts from southern China to the northeast coast [3]. Ten coastal and six inland provinces in China are plagued by typhoon-related disasters, out of a total of 28 provinces with more than 250 million people impacted by typhoons [4]. Typhoons are thought to have incurred a gross net economic loss of 28.34 billion dollars in China between 1992 and 2010. Typhoons cost China an estimated 5.6 billion dollars a year in direct economic losses [5]. Meanwhile, China’s coastal regions’ GDP now accounts for more than 60% of the country’s overall GDP, and their population accounts for 40% of the country’s total population [6].

A TC’s damage is primarily determined by its strength, duration, and location. Typhoons’ location and severity could be forecast in advance thanks to helpful real-time satellite measurements and prognostic advice from operational numerical weather prediction (NWP) models [7]. As a result, to assist government disaster response and minimize the likelihood of loss of life and property, a prompt and accurate prediction of the track, landfall site, intensity adjustments, and associated rainfall is needed [8–11].
The capability of NWP has grown over the last two decades for many reasons [12], such as the progresses in NWP models, the improvement of advanced data assimilation (DA) techniques, and the abundance of remote sensing data, primarily including radar and satellite data [13–19]. Despite recent advances in NWP, correctly forecasting TCs remains a difficult task, particularly given the fluctuating wind speed of typhoon [20].

In NWP, DA is critical in making good use of available observations in order to achieve improved initial conditions and boost subsequent forecasts. Remote sensing data from space-based microwave instruments aboard polar-orbiting satellites has proven to be extremely useful in NWP. Several studies have shown that assimilating satellite-derived wind, temperature, and moisture profiles into initial TC analyses will greatly increase the accuracy of track, intensity, and structure predictions [21–23].

The satellite radiances can be assimilated into NWP models in two ways. In the first example, satellite radiances are transformed into temperature and humidity atmospheric variables using physical or mathematical retrieval techniques, and then the data are assimilated. Temperature and moisture profiles in the atmosphere have been found to affect TCs [23–25]. In the second method, satellite radiances are directly assimilated into NWP models using three-dimensional variation (3DVAR), 4DVAR, various forms of Kalman, particle filter, and hybrid assimilation approaches. The 3DVAR DA technique on the Weather Research and Forecasting (WRF) model was widely used to assimilate various satellite radiances to improve the typhoon track and intensity forecasting, such as Shen and Min [17] with Advanced Microwave Sounding Unit-A (AMSU-A) radiance data, Zou et al. [26] with clear-sky radiances from the GOES-13/15 geostationary satellites, Yang et al. [27] with Advanced Microwave Scanning Radiometer 2 radiance data, and Xu et al. [28] with Himawari-8 imager radiance data.

However, the performance of satellite radiance DA in limited-area modeling systems, especially for satellite data from different sensors, is still debatable. The Advanced TIROS Operational Vertical Sounder (ATOVS) suite consists of the High Resolution Infrared Radiation Sounder, the AMSU-A, the Microwave Humidity Sounder (MHS) onboard National Oceanic and Atmospheric Administration (NOAA), and MetOp satellites. Because of the various satellite orbits and observed angles, satellite sensors have different data coverage when tracking a given typhoon, resulting in different assimilation effects on the typhoon path and strength prediction.

To better understand the variations in assimilation effects and impact mechanisms of different satellite platforms and microwave data, especially the assimilation effect differences and influence mechanisms, the assimilation of AMSU-A and MHS satellite radiance data on the forecast of Typhoon Megi (2016) using the WRF 3DVAR method is conducted in this study. The impact mechanisms of DA adjustments to the initial fields and assimilation increment analysis of each physical quantity field are investigated. A detailed analysis of the data quality control (QC) procedures will also be addressed. The data and methods are described in Section 2. Assimilation tests with different satellites and their combined assimilation are designed in Section 3. The effect of AMSU-A and MHS DA on Typhoon Megi (2016) track and strength forecast results is examined in Section 4. Finally, the conclusions are outlined.

2 Methodology and data

2.1 WRF model and WRFDA system

The WRF [29] Model version 3.8.1 is used in this prediction. It is a non-hydrostatic, limited-area primitive equation model with a variety of physical parameterization schemes. The physical options in the WRF used in this analysis are as follows: the WRF Single-Moment 6-class microphysics scheme [30], the New Kain-Fritsch cumulus convection parameterization scheme [31], MM5 similarity for surface layer physics [32], Noah land surface model for land surface processes [33], and the Yonsei University planetary boundary layer scheme [34]. The Rapid Radiative Transfer Model [35] and Dudhia scheme [36] were used for longwave and shortwave radiation, respectively. The model domain is centered 25°N and 130°E with a grid spacing of 30 km and 200 × 125 grid points (Figure 1). There were 35 vertical levels in the model, with the top of the atmosphere at 50 hPa.

![Figure 1: Computational domain for the experiments.](image-url)
The WRF three-dimensional variational (3D-Var) data assimilation (WRFDA) [37] system was used in this study. It is capable of assimilating data from a variety of observational platforms, including satellite-based radiance measurements. All DA experiments are carried out using the 3DVar method. The WRF 3DVar approach [38] is based on the minimization of a cost function defined as follows:

\[ J(x) = \frac{1}{2} \left| (x - x_b)^T B (x - x_b) + (y - H(x))^T R (y - H(x)) \right| \]

where \( x \) represents analysis field, \( x_b \) represents background field, \( y \) represents observation field, and \( B \) and \( R \) are background error (BE) covariance and observation error covariance, respectively. The observation field and the background field must be compared using observation operator \( H \), which projects model variables into observation space. In the case of radiance assimilation, the community radiative transfer model (CRTM) [39], developed by the Joint Center for Satellite Data Assimilation (JCSDA) was used as the forward operator to simulate radiances. The CV3 default option in WRFDA 3DVAR used the National Meteorological Center method [40] to obtain BE covariance statistics for five control variables including the stream function \( \psi \), the unbalanced temperature potential \( \psi_u \), the unbalanced temperature \( T_u \), the pseudo-relative humidity \( q \), and the unbalanced surface pressure \( P_{su} \). The averaged 24 and 12 h forecast differences that vary at the same time are used to approximate the BE covariances. Additionally, the default observation errors of each satellite channel provided by WRFDA were used in this study.

2.2 ATOVS data

ATOVs instruments are sensors on the NOAA series of polar-orbiting satellites. The AMSU-A is a multi-channel radiometer with 15 channels operating at frequencies ranging from 23.8 to 89.0 GHz that is primarily used to provide temperature profiles. The swath width of each channel is 2,343 km, with 30 pixels measured in each swath and a footprint of around 24 km radius at nadir [17]. The MHS is a five-channel cross-track scanning microwave radiometer of the ATOVS instrument suite that is designed to retrieve profiles of atmospheric water vapor. It operates in the 89–190 GHz frequency range. Its swath distance is approximately 1,920 km, and each scan line has 90 pixels across the earth view, corresponding to a circle of diameter approximately 16 km at nadir [41,42].

AMSU-A and MHS are currently onboard the NOAA (NOAA 15–19) and the MetOp (MetOp A–C) satellite series providing the measurements of the atmospheric temperature and humidity. The radiances measured by AMSU-A onboard NOAA-15 and -18, as well as MHS onboard NOAA-18, are used in this article.

3 Experimental setting

To assess the impact of AMSU-A and MHS radiance assimilation, Typhoon Megi (2016) was selected. In late September 2016, Typhoon Megi (2016) was a wide and strong TC that affected Taiwan and eastern China. It developed from a tropical depression near Guam at 1800 UTC on 22 September 2016 in the western Pacific Ocean. The Japan Meteorology Agency (JMA) named it Megi on 23 September after it pushed mostly northwestward and was upgraded to a tropical storm. This tropical storm was upgraded to a strong tropical storm at 1200 UTC on 24 September 2016, and then to a typhoon category in 6 h. Megi’s amplitude is well sustained for about 30 h. Prior to landfall, Megi-2016 attained its peak strength at 1800 UTC on 26 September 2016, with 10 min maximum sustained winds of 155 km/h. Megi-2016 then made landfall over Hualian, Taiwan, at 0600 UTC on 27 September 2016 and then crossed the Taiwan Strait and making a second landfall as a weaker typhoon in Hui’an County, Fujian Province, China, at 2040 UTC on 27 September [43].

The 6-hourly National Centers for Environmental Prediction (NCEP) analyses with 1° × 1° resolution were used for the WRF model boundary conditions. To eliminate the effect of radiance in the first guess field from NCEP analysis data, 6 h spinup run was performed from 0600 to 1200 UTC on 25 September 2016. The experiment design consists of six simulations that are summarized in Table 1. The control (CTL, no assimilation) experiment was performed with initial conditions at 1200 UTC on 25 September 2016 and run for 60 h.

The other five DA experiments (A15, A18, A58, M18, and AM18), which assimilate radiances from the AMSU-A onboard NOAA-15, AMSU-A onboard NOAA-18, both AMSU-A onboard NOAA-15 and -18, MHS onboard NOAA-18, both AMSU-A and MHS onboard NOAA-18, respectively, were conducted to assess the assimilation impact of different microwave datasets.

Experiments A15, A18, and A58 were designed to compare how the assimilation of AMSU-A microwave data onboard various platforms affected typhoon path and intensity simulations. In contrast, experiments A18, M18, and AM18 are aimed to compare the effects of assimilating combining radiance data from AMSU-A and MHS.
Since there was no observation of NOAA-19 in the study area at assimilation window time, only NOAA-15 and NOAA-18 data were selected for comparative analysis in this article.

In order to contain sufficient data, satellite observations within ±3 h assimilation windows around 1200 UTC on 25 September 2016 were used for assimilation experiments, and the background for assimilation derived from the previous 6 h WRF forecast. After that, the experiments were run in forecast mode for 60 h, beginning at 1200 UTC on 25 September 2016.

4 Results

4.1 QC procedures

The satellite data was subjected to a series of QC procedures, including channel selection, cloud, precipitation detection, data thinning, and bias correction. All of these QC techniques were aimed at eliminating radiances that were significantly different from CRTM simulations.

Channels 1–4 and 15 from AMSU-A were rejected because their weighting function peaks were near the Earth’s surface. Since the WRF model top is approximately 50 hPa, AMSU-A channels 10–14 in assimilation were omitted because they have a higher contribution at the model’s top levels. Channels 1 and 2 of MHS are two window channels that are most impacted by radiation from the Earth’s surface in clear sky situation, but also by the water vapor emission and ice scattering if clouds are present [42]. In summary, the AMSU-A channels 5–9 for NOAA-15 and 5–8 for NOAA-18, as well as MHS channels 3–5, were chosen in radiances assimilation experiments.

Due to the limb impact of the data, observations at limb scan locations (Field of views of 1–3 and 28–30, 1–8 and 83–90, for AMSU-A and MHS, respectively) are not utilized. Furthermore, precipitation-affected AMSU-A and MHS data were excluded by eliminating data where the absolute value of the window channel innovation exceeded a 3K threshold (for channels 1 and 15 of the AMSU-A and channels 1 and 2 of MHS, respectively). AMSU-A and MHS radiances affected by liquid and/or ice clouds were eliminated for liquid water path >0.2 g/m². To prevent potential correlations between horizontally adjacent observations, the raw AMSU-A and MHS radiance data are thinned using a 60 km thinning mesh. Table 2 lists the selected channels as well as the number of AMSU-A and MHS observations before and after QC. Following the completion of all QC

<table>
<thead>
<tr>
<th>Platform</th>
<th>Sensor</th>
<th>Points after thinning</th>
<th>Channel</th>
<th>Points eliminated by QC</th>
<th>Retained points after QC</th>
</tr>
</thead>
<tbody>
<tr>
<td>NOAA-15</td>
<td>AMSU-A</td>
<td>1,430</td>
<td>5</td>
<td>639</td>
<td>791</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>6</td>
<td>613</td>
<td>817</td>
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<tr>
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<td>487</td>
<td>943</td>
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<td></td>
<td></td>
<td>8</td>
<td>506</td>
<td>924</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>9</td>
<td>769</td>
<td>661</td>
</tr>
<tr>
<td>NOAA-18</td>
<td>AMSU-A</td>
<td>3,073</td>
<td>5</td>
<td>1,500</td>
<td>1,573</td>
</tr>
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<td></td>
<td></td>
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<td>1,018</td>
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<td>7</td>
<td>895</td>
<td>2,178</td>
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<td></td>
<td></td>
<td>8</td>
<td>1,038</td>
<td>2,035</td>
</tr>
<tr>
<td>MHS</td>
<td></td>
<td>4,027</td>
<td>3</td>
<td>1,709</td>
<td>2,318</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4</td>
<td>1,845</td>
<td>2,182</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>5</td>
<td>2,067</td>
<td>1,960</td>
</tr>
</tbody>
</table>
operations, the proportions of data utilized in the DA system were reduced by 30–50% for various channels.

Figure 2 shows the coverages of AMSU-A channel 6 (a and c) and MHS channel 5 (e) brightness temperatures data assimilated on 1200 UTC on 25 September 2016, following thinning and quality checking. Figure 2b, d, and f also shows the simulated brightness temperatures of the respective channel derived using the CRTM model.

Before direct radiances assimilation, satellite data must be simulated by modeling the background field. However, the simulated bright temperature frequently differs from the observed bright temperature due to systematic errors in the observations, in the background or analytical fields, and in the radiative transfer model. Radiance bias correction is required for satellite radiance DA. With prediction parameters such as air mass characteristics and scan location, the variational bias correction [44] scheme is utilized in this study. By introducing the coefficients of the bias revision forecast operator as control variables into the assimilation system, the predictor coefficients are dynamically updated in real time to dynamically estimate the revised observation bias based on satellite observations and unbiased conventional observations across the full assimilation interval. Scatter graphs of observed (OBS) against CRTM simulated brightness temperatures at 1200 UTC on 25 September 2016, for channel 6 of AMSU-A from NOAA-15, -18, and channel 5 of MHS from NOAA-18 are shown in Figure 3. The mean (MEAN), standard deviation (STDV), and root mean square error (RMS) are given in the lower right corner of the figure, respectively.

In comparison to the bias before correction (no BC) for channel 6 of AMSU-A from NOAA-15/-18, the RMS of background (BAK) with bias correction (with BC) dropped from 3.869/0.878 to 0.342/0.316 (by around 91.2/64.0%). With radiance DA, the RMSE of analysis (ANA) was further lowered to 0.280/0.185 and the STDV to 0.241/0.183. The RMSE and STDV of ANA for channel 5 of MHS were lowered by roughly 36.7 and 32.7%, respectively, as compared to the data of BAK following BC.

Figure 4 shows the histogram distribution that corresponds to Figure 3. The peak of observation minus background (OMB) is at −0.1 to 0.2 K, suggesting that the bias correction minimizes the difference between the simulated bright temperature of the background and the observation field. Because of the assimilation effect, the WRFDA analysis field in the third column derived after assimilation of the satellite observations is closer to the measured brightness temperature than the background field. The peak of observation minus analysis (OMA) values was closer to 0 K than OMB in the second column.

4.2 Impact on Typhoon Megi (2016) track and intensity forecast

The performance of the 60 h Typhoon Megi (2016) path and intensity forecasts (without and with AMSU-A and MHS DA) was compared to the best available data (BST) from the China Meteorological Administration (CMA) TC database (http://tcdata.typhoon.org.cn). Every 6 h, the track record and intensity data of typhoons are obtained, including the typhoon’s center position (latitude and longitude), maximum wind speed (MSW) (10 min average), and central sea level pressure (SLP).

Figure 5 shows the forecast track and average location errors for Typhoon Megi (2016) based on the six trials. The characters “BST,” “CTL,” “A15,” “A18,” “A58,” “M18,” and “AM18” in the figure represent the best typhoon observation data from the CMA, the control experiment without assimilation, the assimilation of NOAA-15 AMSU-A, the assimilation of NOAA-18 AMSU-A, the assimilation of both NOAA-15 and -18 AMSU-A, the assimilation of NOAA-18 MHS, and the assimilation of combined AMSU-A and MHS onboard NOAA-18, respectively.

As can be observed in Figure 5a, all of these studies showed a similar trend in track prediction when compared to the best route of Typhoon Megi (2016). Overall, the tests A15, M18, and CTL have a south twist, whereas the other three have a north twist to some extent. During the early prediction periods, the Typhoon locations are quite near to the best track measurements. The track errors of all trials, on the other hand, grow with the projected lead time.

We calculated the track errors for the six assimilation experiments (Table 3) and plot them as a function of forecast hour in Figure 5b for a more thorough analysis. When compared to the CTL run (Bias of 103.76 km and RMSE of 123.95 km), the data demonstrate that virtually all DA tests helped to reduce prediction track errors. During the 60 h model integration, the projected track from the A15 experiment (Bias of 60.26 km and RMSE of 69.01 km) matches more closely with the best track data than the other five trials. However, the A18 and A58 experiments using NOAA-18 AMSU-A radiance assimilation simulated the typhoon’s first landfall better than the A15 trial. When comparing the assimilation results of AMSU-A and MHS onboard NOAA-18, the A18 simulations’ track and landfall position are closer to observation than M18 for the whole 60 h simulation. The typhoon track in M18 has the minimum error, with a Bias of 31.77 km and an RMSE of 41.84 km, before 30 h of model integration, followed by A15, which is closer to the optimal track than CTL. However, after 30 h of integration, M18’s track mistakes skyrocke,
Figure 2: Brightness temperatures (K) of AMSU-A channel 6 from NOAA15 (a) and NOAA18 (c) and MHS channel 5 from NOAA18 (e) at the analysis time of 1200 UTC on 25 September 2016 after QC. The brightness temperatures of the relevant channel estimated by CRTM are shown in the right column (b, d, and f).
eventually overwhelming the other five studies. The predicted inaccuracy increases dramatically after 60 h.

In brief, MHS assimilation has a greater favorable influence in short-range prediction (30 h lead time) than in long-range prediction (beyond 60 h) and NOAA-15 AMSU-A assimilation leads to the best results for overall performance.

Similarly, in Figure 6, we depict the predicted minimum sea level pressure (MSLP) and MSW as a function of forecast...
lead time. The errors of forecast MSLP and MSW from various experiments over time in the 60 h are also shown in Figure 6 and Table 4. The MSLP and MSW were predicted to be of similar strength in all experiments.

For the MSLP forecast, all experiments with radiance assimilation except M18 are closer to the best track data than the CTL experiment. According to RMSE, A15 has the fewest mistakes, with a Bias of 6.76 hPa and an RMSE of
8.19 hPa, followed by AM18, A18, A58, and CTL. M18 is the only one with a larger error than CTL. However, the MSLP error of M18 is less than CTL in the first 18 h of model integration, demonstrating that MHS assimilation is beneficial for a short lead time.

A15 outperforms A18 and A58, demonstrating that assimilation satellite data from several platforms are not always superior than data from a single satellite. A15 has the least mistakes overall, with a Bias of 7.80 m/s and an RMSE of 8.34 m/s, according to the MSW prediction. However, M18 is superior to A15 for the first 30 h integration, but this preference flips beyond that time. This refers to the fact that assimilation of MHS offers a short-term advantage for maximum wind speed forecasting, but has a long-term detrimental influence (the last 30 h). The uncertainty of the impact of MHS needs to be further investigated. Overall, both AMSU-A and MHS satellite radiances assimilations have a positive impact on the track and intensity forecast by improving initial temperature and moisture conditions [17,46–48].

### 4.3 Analysis of the impact of assimilation on meteorological elements

In order to further understand the mechanism of assimilation on the path and intensity of Typhoon Megi (2016), the adjustment of fundamental meteorological components before and after assimilation, as well as the incremental analysis of each physical quantity field, were examined by minusing the regional average value of the background fields at each height with the corresponding analysis fields (Figure 7).

For initial temperature, humidity, latitudinal, and longitudinal winds, as shown in Figure 7, the magnitude

![Figure 5: Forecast track (a) and mean track error (b) of Typhoon Megi (2016) simulated initial at 1200 UTC on 25 September 2016 for different experiments.](image)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Bias (The first 30 h integration)</th>
<th>RMSE (The first 30 h integration)</th>
<th>Bias (The last 30 h integration)</th>
<th>RMSE (The last 30 h integration)</th>
<th>Bias (The 60 h integration)</th>
<th>RMSE (The 60 h integration)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTL</td>
<td>49.01</td>
<td>57.57</td>
<td>158.92</td>
<td>163.50</td>
<td>103.76</td>
<td>123.95</td>
</tr>
<tr>
<td>A15</td>
<td>45.07</td>
<td>49.77</td>
<td>78.76</td>
<td>85.56</td>
<td>60.26</td>
<td>69.01</td>
</tr>
<tr>
<td>A18</td>
<td>69.25</td>
<td>74.84</td>
<td>111.94</td>
<td>117.10</td>
<td>90.87</td>
<td>99.18</td>
</tr>
<tr>
<td>A58</td>
<td>61.35</td>
<td>65.71</td>
<td>101.32</td>
<td>107.14</td>
<td>83.02</td>
<td>90.87</td>
</tr>
<tr>
<td>M18</td>
<td><strong>31.77</strong></td>
<td><strong>41.84</strong></td>
<td>179.53</td>
<td>191.42</td>
<td>107.50</td>
<td>142.41</td>
</tr>
<tr>
<td>AM18</td>
<td>68.53</td>
<td>74.01</td>
<td>121.73</td>
<td>128.57</td>
<td><strong>96.19</strong></td>
<td><strong>106.63</strong></td>
</tr>
</tbody>
</table>

Bold indicate the smallest bias or RMSE among all assimilation experiments.
of adjustment for each element after assimilation occurs mostly above 500 hPa. This could be related to the vertical weighting distribution of the satellite information.

MHS had a higher influence on upper-level relative humidity than AMSUA. The NOAA15 experiments test indicated mostly cooling and humidity reduction in the lower layers below 700 hPa, whereas the NOAA18 test had minimal effect in the lower layers, mainly showing cooling and humidity increase above 500 hPa.

Because the overall large-scale regional average does not directly reflect how the basic elements affect typhoon movement and intensity changes, analysis of the physical quantity fields that have a large impact on typhoon

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Bias of MSLP (hPa)</th>
<th>RMSE of MSLP (hPa)</th>
<th>Bias of MSW (m/s)</th>
<th>RMSE of MSW (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTL</td>
<td>9.57</td>
<td>10.95</td>
<td>8.89</td>
<td>9.29</td>
</tr>
<tr>
<td>A15</td>
<td>6.76</td>
<td>8.19</td>
<td>7.80</td>
<td>8.34</td>
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<tr>
<td>A18</td>
<td>7.96</td>
<td>9.56</td>
<td>8.33</td>
<td>9.04</td>
</tr>
<tr>
<td>A58</td>
<td>8.12</td>
<td>9.61</td>
<td>8.66</td>
<td>9.44</td>
</tr>
<tr>
<td>M18</td>
<td>10.55</td>
<td>12.34</td>
<td>7.88</td>
<td>8.59</td>
</tr>
<tr>
<td>AM18</td>
<td>8.19</td>
<td>9.52</td>
<td>8.61</td>
<td>9.50</td>
</tr>
</tbody>
</table>

Bold indicate the smallest bias or RMSE among all assimilation experiments.
movement and intensity changes is required to investigate assimilation mechanisms. The difference between the analysis field after assimilation (i.e., the initial field of the assimilation) and the background field before assimilation (i.e., the initial field of the CTL test) is known as the assimilation analysis increment. The SLP field, 500 hPa height and wind field, and 200 hPa wind field are chosen for the assimilation increment analysis.

Figure 8 shows the distributions of the SLP field (a) and the analysis increment distributions for assimilation experiments (b–f). The red dot represents the observed typhoon position, whereas the green dot represents CTL simulated typhoon position. As shown in the analysis increment distributions for assimilation experiments (b–f), there is a clear negative zone around the typhoon’s central location, and a circular positive zone around the typhoon’s eye, with a further circular positive zone beyond the positive zone, indicating further strengthening after the moment of assimilation analysis. The positive zone on the southeast side of the typhoon eye area has higher values than the positive zone on the west side, and the pressure gradient

Figure 7: Distribution of the mean vertical deviation of regional average temperature (a, in °C), relative humidity (b, in %), latitudinal wind (c, in m/s), and longitudinal winds (d, in m/s) after DA.
force points to the northwest, indicating that the typhoon will move in a northwesterly direction. The positive regions of A18, A58, and AM18 are substantially larger than those of A15 and M18, indicating that the former is heading northwesterly. This is consistent with the simulated in the previous description, suggesting that the assimilation test is a better simulation of typhoon intensity and intensity trends at the initial moment than the CTL test.

The 500 hPa geopotential height and wind field and the analysis increment distributions for assimilation experiments at analysis time are given in Figure 9. The shaded colors represent the geopotential height field (in gpm) and the vector arrows represent wind field. As shown in Figure 9a, the typhoon is bordered to the north by subtropical high pressure, and travels westward due to the easterly wind belt. The initial wind field was altered in all sets of assimilation testing by changing the 500 hPa wind field structure. Comparing the analysis increments (Figure 9b–f) of the assimilation experiments shows that the geopotential height and wind fields around the typhoon area are adjusted significantly more in A18 than in the other sets of experiments, and the incremental distribution pattern after the combined assimilation of A15 or M18 is more or less the same as in A18, indicating that the contribution of AMSUA on NOAA18 to the assimilation is more pronounced.

Figure 8: SLP field (a) and the analysis increment distributions for assimilation experiments (b–f) at analysis time.
The higher level westerly jet is also strongly connected to typhoon intensity. In general, if the upper-level westerly jet is located to the north of the typhoon, the outflow of the typhoon’s upper-level dispersion is aided by the strengthening of the upper-level westerly jet, which increases the wind-pump effects and helps the typhoon to grow and intensify more. As seen in Figure 9a, the wind speed on the north side of the typhoon is substantially greater than on the south side, and the wind speed inside the eye area of the typhoon simulated in the CTL run is low, below 12 m/s, but beyond the eye area, there are areas of strong winds exceeding 24 m/s.

Meanwhile, north of 25°N, there exists a zone of fast westerly winds with a central wind speed of 24 m/s or greater. The high westerly jet promotes the dispersion and outflow of the typhoon’s top levels, implying that the typhoon’s strength in the CTL test would be increased. Comparing the incremental analysis of assimilation tests (Figure 9b–f).

As can be seen, each test has negative incremental zones to the east and west and positive incremental zones to the north and south, while the positive incremental zone to the north just corresponds to the strong outflow zone to the north of the typhoon in Figure 9a, indicating

![Figure 9](image-url): The 500 hPa geopotential height and wind field (a) and the analysis increment distributions for assimilation experiments (b–f) at analysis time.
the intensification of the typhoon. The north side of A15 and M18 has a substantially larger intensity of the positive incremental zone than the south side, suggesting that the typhoon strength simulated by A15 and M18 is stronger than the CTL test. Moreover, the positive northern incremental zone in M18 is higher than that of A15, indicating that the simulated typhoon intensity of M18 is higher than that of A15 (Figure 10). This shows that M18 has the best assimilation impact and the closest correction to the measured upper 200 hPa wind field at the early simulation time period, which is consistent with the assimilation experiments in Section 4.2.

5 Conclusions

Using the WRF and its 3DVAR modeling system WRFDA, this study explored the effects of assimilation of AMSU-A and MHS microwave data from NOAA-15 and NOAA-18 on Typhoon Megi (2016) predictions.

Each experiment’s assimilation impact was investigated by comparing the simulated typhoon movement routes and intensities. The adjustments of fundamental meteorological components before and after assimilation, as well as the increment of assimilation analysis of each physical quantity field, were also examined in
order to better understand the mechanism of assimilation on typhoon course and intensity. The main results are as follows. Before assimilation of observational radiance, data QC is required. For AMSU-A and MHS, the bias correction lowered the mean bias of the innovations. The RMSE of OMA was always lower than that of OMB, showing that WRFDA analysis improved as a result of assimilation.

The results of the study reveal that assimilating the satellite radiances improved the track and intensity forecast of Megi (2016). Overall, the best performance comes from NOAA-15 AMSU-A radiance assimilation, whose Megi (2016) track and intensity forecast match the observations better than the other five experiments during the 60 h model integration. However, the assimilation of M18 improved the short- to medium-term forecast (30 h lead time). But, the MHS assimilation had a detrimental influence on the long-range prediction (the last 30 h). The uncertainty of MHS’s influence needs to be examined further. The findings show that satellite DA from several platforms is not always superior to data from a single satellite.

The level of adjustment for each assimilation test occurs mostly above 500 hPa for the initial field temperature, humidity, latitudinal, and longitudinal winds. MHS has a stronger influence on upper-level relative humidity than AMSUA. Assimilation increment analysis of the SLP field, 500 hPa height and wind field, and 200 hPa wind field shows that all of the assimilation experiments are adjusted in relation to the backdrop field, which impacts typhoon movement route and intensity fluctuation.

WRFDA can also use more sensors from orbit and geostationary meteorological satellites to boost prediction accuracy. Furthermore, if cloudy-radiance data can be employed in assimilation in the future, forecasting skills might be greatly enhanced. For additional improvements in futility, more sophisticated assimilation approaches, such as 4DVAR and ensemble-based approaches might be used.

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