Reply to reviewer 1

General comments,

This study implemented the assimilation of JMA himawari-8 AHI radiance with the framework of the mesoscale numerical model WRF and its three dimensional variational assimilation system (3DVAR) for the analysis and prediction of typhoon "Soudelor". The results are impressive in terms of the AHI radiance simulation and the forecast skill of the tropical cyclone for both the track and intensity. This action is meaningful, when geostationary meteorological satellite radiances provide valuable information of the weather systems with high spatial and temporal resolutions. However, there are several issues to be fixed to better clarify the methodologies and results.

Specific comments,

1) section 4.1 Please explain why there is some oscillation in the variation of the gradient with increasing iteration?

Reply:3DVAR works by minimizing the cost function through iterations, which will not guarantee the decrease for the gradient for each step monotonously. The similar oscillation in the gradient can be also found in Wang and Liu (2019).

Reference:

Wang, S. and Z. Liu, 2019: A radar reflectivity operator with ice-phase hydrometeors for variational data assimilation (version 1.0) and its evaluation with real radar data, Geosci. Model Dev., 12, 4031–4051.

2) This study assimilates clear-sky radiances. However, Figure 6 gives a very confusing picture. The data over the cloudy regions are presented in the observations. Radiances over the cloudy region are still calculated. Please provide the procedure for the verification results in Fig.6 with all the data shown as only clear-sky data are applied.

Reply: The simulation of the brightness temperature is conducted as one of the verification methods. More explanation is added as “It should be pointed that even only parts of the AHI radiance data are applied after quality control in the data assimilation, the radiative transfer model is able to simulate the brightness temperature for all the pixels with the background and the analysis respectively for the verification purpose. The similar verification method is also applied in Yang et al., (2016).”

Reference:

Yang, C., Liu, Z., Bresch, J., Rizvi, S. R. H, Huang, X.-Y., and Min, J. AMSR2 all-sky radiance assimilation and its impact on the analysis and forecast of Hurricane Sandy with a limited-area data assimilation system, Tellus A: Dynamic Meteorology and Oceanography, 68, 1, 2016.

3) Please point out the reason channel 10 yield smaller RMSE?

Reply: It is found from Fig. 8g that the simulated brightness temperature for assimilated pixels fit best with the observation compared to other two channels, which is likely related to strict cloud detection scheme for channel 10 with rather lower detecting peak. The authors have plotted the weighting function for the three water vapor channels. Thus, the manuscript is revised as “Among them the RMSE of channel 10 is smallest as 0.234 K in Fig. 8i, which is likely related to strict cloud detection scheme for channel 10 with rather lower detecting peak (Wang et al., 2018).”

Technical corrections

1) L35 use accurate instead of exact

Reply: Thanks for the helpful advice. Corrected at line 43

2) L39 together with the microphysics and ..

Reply: Thanks. Added.

3) L54 radiance data are ..

Reply: Thanks. Corrected.

4) L104 positive impact

Reply: Thanks for pointing it out. Corrected.

5) L106 Please reorganize the sentence “Wang, et al (2018). . .”and check this kind of problem thoroughly for the whole manuscript

----

Reply: Thanks for the helpful advice. The sentence is reorganized and the language is further edited by an English native speaker for the whole manuscript.

6) L112 previous researches

Reply: Corrected.

7) L147 This work focuses. . . Please check this problem for the whole manuscript

----

Reply: Corrected. We also improved these expressions with active words to an objective statement. Revisions can be found by tracks in detail.

8) L243 Please change the word rarefy

Reply: Thanks for the helpful advice. We use thin to replace rarefy at line 283, now the sentence is “20 km is chosen to make thinning of AHI radiance data”.

9) L261 Fig. 6a shows or provides. Please fix this problem for the whole manuscript

----

Reply: Thanks. corrected.

10) L262 of channel 8

Reply: corrected.

11) L332 after the bias correction.

Reply: Thanks. This expression is corrected as “before and after the bias correction”, see line 353.

12) L350 are also calculated

Reply: Thanks. This expression is corrected as “The RMSEs of the simulated brightness temperature by the NWP model before and after the assimilation are also calculated against the AHI radiance observations.” at line 370.

13) L427, this manuscript. . .

Reply: Thanks for the helpful advice. This expression is corrected as “In this study, the AHI radiance data assimilation is conducted under the clear sky condition.” at line 460.

Reply to reviewer 2

This paper studies the effect of assimilating satellite observations on the prediction of typhoon. The predictions are made with WRF model, and initialization is performed by its 3D-VAR system. The technique is not new but the claim of novelty is that the system incorporates the newest data from a geostationary (in contrast to polar-orbiting) satellite, namely Himawari-8. Improvements in the predicted track and intensity of typhoon Soudelor are found with the assimilation of the satellite data. This is a timely study with potentially useful results. Nevertheless, clarifications are needed on some of the technical details:

(1) The conclusion of this work relies on a small number of runs without exploring the dependence of the prediction on tunable parameters in WRF-3DVAR, for example those for the spatial correlation length and the scale of background variance. Previous studies have shown that the predictions of typhoon/hurricane tracks depend on those parameters (Xu et al. 2019, Meteorol. Appl., doi:10.1002/met.1820; Chou and Huang 2011, Adv. Meteorology, doi:10.1155/2011/803593). If this study just uses the default setting of those parameters, it would be useful to provide justifications or demonstrate that the results are robust with respect to tuning of the parameters.

Reply: Thanks for the pointing it out. The sentences are added as “The length scale and the variance scale are set to be 0.5 and 1 respectively after several sensitivity experiments conducted on tuning the background error. Similar conclusions are also found in Shen and Min (2015) with the scale factors related to the static background error covariance.” to make it clear.

(2) Since only clear-sky data is assimilated, one would guess that most of the satellite data over the cloudy area surrounding the core of typhoon are rejected. Yet, from Figs. 10(a) and 10(b) it appears that some distinctive small-scale structures (e.g., multiple spiral bands of high humidity) are created over the vortex core of the typhoon after the assimilation of satellite data. Are those structures artificial (e.g., due to numerical schemes of the model) rather than a realistic effect of assimilation of satellite observation? Related to this, it would also be interesting to compare the detail of the wind field near the center of the typhoon, but the vectors in Fig. 10 are hard to read. It would be useful to modify the figure to improve clarity.

Reply: We agreed that most of the AHI clear-sky radiance data over the typhoon core area are rejected. However, the environment can be adjusted to some extent with the obtained observations. The model status in the cloudy area will also be modified with the spatial correlation in the background error covariance. The similar findings for small-scale information in the cloudy area can also be referred in Wang et al., (2018). Fig. 10 is also replotted to improve the clarity. Related explanations are also added as “It should be pointed out that the model status in the cloudy area are modified due to the spatial correlation in the background error covariance. The similar findings for small-scale information in the cloudy area can also be referred in Wang et al., (2018)."

(3) Figure 11(a), which shows the key result for typhoon tracks, is hard to read. The 3 tracks all look like solid lines that it is not possible to identify which is which. There seems to be random drawings in the background but it is not clear what they are (continental boundaries?) The labeling at left for the ordinate is cut off. Also, only one set of predictions is shown. What about other predictions made at different initial times? Do they exhibit similar behaviors? [This is also related to the comment in (1) concerning the robustness of results, given the small number of runs.]

Reply: Thanks for the helpful advice. We replotted the tracks with colorful lines in the revised manuscript. The random drawings in the background is also removed. The labeling at left is also kept. The forecast from 0000 UTC 02 August 2015 is also added for the track in Figure 12a. The forecast ranges are extended from 18 hours to 48 hours. In addition, the mean track errors, maximum surface wind speed error, and the minimum sea level pressure error are also calculated for two forecasts initialized at 0000 UTC and 0600 UTC presented in Figure 12c, and Figure 13.

Reply to reviewer 3

Overview: In this manuscript, the authors have tried to attempt to see the effect of data assimilation of AHI data for Typhoon Soudelor by using WRF-3DVAR. Perhaps, this data assimilation method has been widely used by many typhoon researchers, but this AHI data assimilation would be novel because Himawari-8 satellite provides more segmentalized bands compared to previous MTSAT series. I could see the effect of this AHI data assimilation, but the forecasting time is too short, which is close to nowcasting. Different initial locations may cause these track errors. Furthermore, the intensity forecasts from both experiments show the same tendency. It may indicate this AHI assimilation is not effective in improving inner-core structures yet. Actually, I could see longer period simulation results rather than 18-h simulations results to see definite improvement of AHI assimilation. Finally, as I suggest many specific comments and editorial comments, the authors seriously consider the English proofreading or carefully review this manuscript before publication. Therefore, since there are some corrections before publication, I would give a major revision opinion. Nevertheless, I think this paper approach is nice.

Specific comments

Lines 119-123: The authors could make the section lists to show how this paper is comprised.

Reply: Thanks for your advice. A new paragraph is added as “Section 2 describes the observations and the data assimilation system. Introductions to the typhoon case and the experimental setup are provided in section 3. The detailed results in terms of the analyses and the forecasts are illustrated in section 4 before conclusions are summarized in section 5.”

Lines 69-72 & 126-128: These sentences are repeated.

Reply: Agreed. Related sentences are deleted in section 1 and section 2.1. The sentence is also reorganized as “As the first new generational geostationary satellite, Himawari-8 plays a pioneering role for the geosynchronous imagers to be launched in US, China, Korea and Europe.” from line 84 to 86. In the second part, we revised as “Himawari-8 satellite was launched by JMA to a geosynchronous orbit on 17 October 2014 and has begun its operational use since 7 July 2015 (Bessho et al., 2016).” from line 153 to 155.

Lines 147-151: I am not sure why the authors put the location of the focuses or purposes in this paragraph? I guess, if the authors put this to Introduction, it would be much clearer than now.

Reply: Thanks for the helpful advice. Following the reviewer's suggestion, these sentences are moved to the 6th paragraph in the introduction part (line 141 to 145).

Lines 147-149: How can we understand that these three moisture channels are sensitive to those levels? Please provide some evidence.

Reply: Thanks. The evidence for the sensitive levels for three water vapor channels is provided as the weighing function in Fig. 1 in the revised manuscript (line 141 to 146).

The sentence is revised as "Our study focuses mainly on assimilating the three water vapor channels (6.2, 6.9, and 7.3μm) since they are very sensitive to the humidity in the middle and upper troposphere and have a certain effect on the lower troposphere. Thus, a large amount of effective atmospheric information can be provided for AHI radiance data assimilation in the troposphere. The weighting functions for the three channels are provided in Fig. 1." in the manuscript.

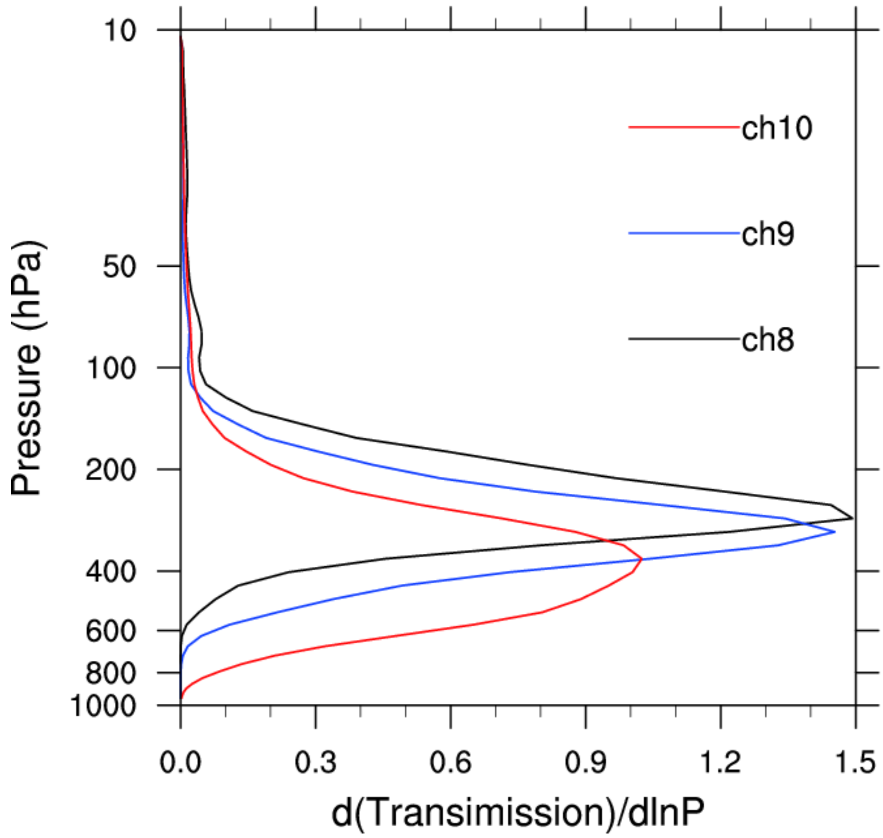


Fig.1 Weighting function for Channel 8, 9, and 10.

Lines 190-200: About re-intensification of Soudelor, I guess, the authors reference JTWC best track data, because there is no such a pattern in JMA best track data. Please specify this information.

Reply: In this study, the best track data are provided by the China Meteorological Administration (Yu et al., 2007; Song et al., 2010). “Related information is added in section 3.1(line 215) and section 4.4 (line 407-408).

Reference:

Yu H, Hu C, Jiang L. 2007. Comparison of three tropical cyclone intensity datasets. Acta Meteorol. Sin. 21: 121–128.

Song J-J, Wang Y, Wu L. 2010. Trend discrepancies among three best track data sets of western North Pacific tropical cyclones. J. Geophys. Res. 115: D12128, DOI: 10.1029/2009JD013058.

Line 200: what the Taiwan channel? Does that mean channel effect? I guess there are some papers discussing that. Please cite some references.

Reply: Thanks for the helpful advice. Taiwan channel means Taiwan Strait, which is a 180-kilometer (110 mi)-wide strait separating Taiwan and mainland China. To avoid misunderstanding, we replace Taiwan Channel with Taiwan Strait at line 227.

Lines 202-203: as mentioned in General comments, the authors should clarify the best track information.

Reply: Agreed. The best track data are provided by the China Meteorological Administration (Yu et al., 2007; Song et al., 2010). “Related information is added in section 3.1(line 215) and section 4.4 (line 407-408).

Section 3.1: Figure 2 needs to make the same period with Fig. 1, and the authors may highlight the specific period (color-shading) according to the purpose.

Reply: Agreed. Figure 2 is replotted from 0000 UTC 30 July 2015 to 0600 UTC 12 August 2015 and the specific period from 1800 UTC 1 August 2015 to 0000 UTC 3 August 2015.

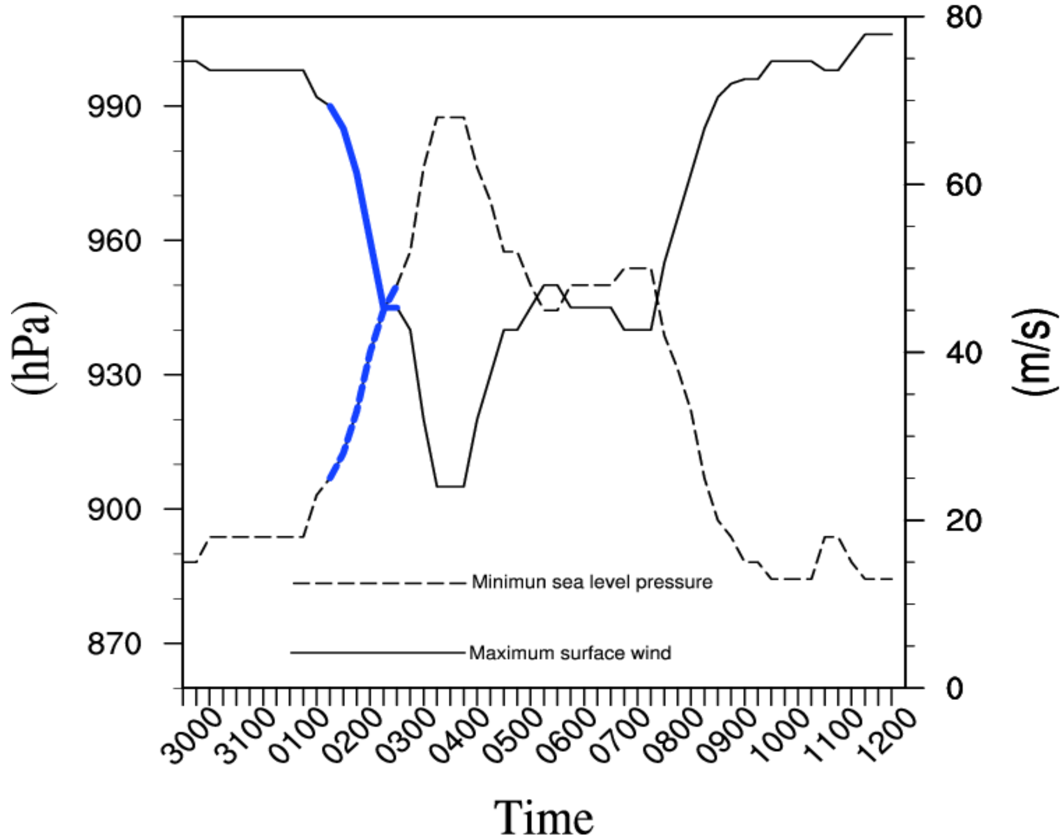


Fig. 3 The time series of the minimum sea level pressure (solid line, unit: hPa) and the maximum surface wind (dash line, unit: m s^{-1}) from 0000 UTC 30 July 2015 to 0600 UTC 12 August 2015.

Line 218: “We use Arakawa C grid in the horizon with a 5 km grid distance.” What is the Arakawa C-grid? I know this grid-structure, but people reading this paper without any background of the WRF model, may not understand this grid-type. If the authors want to use this, please clarify what it is or compare this with other grid-type kinds such as A, B, D, E types (should discuss momentum conservation and other kinds).

Reply: Agreed. Sentences are added to make it clear as “As is known, Arakawa A grid is "unstaggered" by evaluating all quantities at the same point on each grid cell. The "staggered" Arakawa B-grid separates the evaluation of the velocities at the grid center and masses at grid corners. Arakawa C grid further separates evaluation of vector quantities compared to the Arakawa B-grid.” (lin246-250)

Line 219: is this eta levels? Or sigma levels? And is this even vertical spacing?

Reply: Corrected. The eta levels are applied with coarser vertical spacing for the higher levels. The manuscript is revised as “Vertically, it has 41 eta levels using 10 hPa as its top with coarser vertical spacing for the higher levels.” (lin250-252) to make it clear.

Figure 4 appears earlier than Fig. 3; that is not critical, but its order should be sequential. Please rephrase the sentences or remove them.

Reply: Agreed. Thanks for pointing it out. The order of Figure 3 and Figure 4 is changed in the revised manuscript and related sentences are rephased.

Lines 224-225: are there references for the Dudia scheme?

Reply: Thanks for the helpful advice.

The sentence is revised as “The following parameterization schemes are used: WDM6 microphysics scheme (Lim et al., 2010), Grell Devenyi cumulus parameterization scheme (Grell et al., 2002), RRTM (Rapid Radiative Transfer Model) longwave radiation scheme (Mlawer et al., 1997), shortwave radiation scheme (Dudhia et al., 1989), and YSU boundary layer scheme (Hong et al., 2006) .” now from line 254 to 262. Besides, the reference is added as follows,

Dudhia, J. Numerical Study of Convection Observed during the Winter Monsoon Experiment Using a Mesoscale Two-Dimensional Model, Journal of the Atmospheric Sciences, 46, 3077-3107, 1989.

Line 225: It is surprising that YSU PBL is Noh et al. 2003? By the way, the authors said WRFV3.9.1. About the above and this line, the authors should carefully look at the WRF website to cite more appropriate references for the parameterizations.

Reply: Thanks. We double checked the details for all the physics from WRF user guide and make corrections for the reference of YSU PBL as,

Hong S.Y., Noh Y., Dudhia J. A New Vertical Diffusion Package with an Explicit Treatment of Entrainment Processes. Mon. Wea. Rev., 134, 2318-2341, 2006.

Follow the reviewer's suggestion, all the references for the for the parameterizations are also checked.

WDM6:

Lim, K.-S. S., and Hong, S.-Y.: Development of an effective double-moment cloud microphysics scheme with prognostic cloud condensation nuclei (CCN) for weather and climate models. Mon. Wea. Rev., 138, 1587-1612, 2010.

Grell Devenyi cumulus parameterization:

Grell G.A., Dévényi D.: A generalized approach to parameterizing convection combining ensemble and data assimilation techniques, Geophys. Res. Let., 29, 587-590, 2002.

The shortwave radiation scheme:

Dudhia, J.: Numerical Study of Convection Observed during the Winter Monsoon Experiment Using a Mesoscale Two-Dimensional Model, Journal of the Atmospheric

Sciences, 46, 3077-3107, 1989.

The longwave radiation scheme:

Mlawer E.J., Taubman S.J., Brown P.D., et al.: Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave, Journal of Geophysical Research Atmospheres, 102: 16663-16682, 1997.

Sections 3.1 and 4.4 and Fig. 1: What the authors reference the best track data? In the body context and Fig. 1, there is no information on that.

Reply: Agreed. The best track data are provided by the China Meteorological Administration (Yu et al., 2007; Song et al., 2010). "Related information is added in section 3.1(line 215) and section 4.4 (line 407-408).

Section 4.2: I wonder that OMB and OBA indicate the observation (Himawari-8) – background (what background? Where it comes from? And how the authors calculate the brightness temperature of the analytic brightness temperature. Please clarify the methods of how to get the brightness temperature of the background and analytic one. Please put the title of each figure (band-8 micron unit).

Reply: The background for data assimilation is prepared as follows. Firstly, the initial condition and lateral boundary are obtained by the preprocessing module of WRF model with 0.5°×0.5° GFS reanalysis data. Then a 6-hour spin-up is conducted to provide as the background for the data assimilation purpose.

The Community Radiative Transfer Model (CRTM; Liu and Weng, 2006) has been coupled within the WRFDA, which is applied as the observation operator for AHI radiance. The temperature and the humidity information from the model states are essential inputs for CRTM to calculate the simulated brightness temperature (the brightness temperature of the background and analysis).

The simulation of the brightness temperature is conducted as one of the verification methods by comparing with the observed radiance. More explanation is added as "It should be pointed that even only parts of the AHI radiance data are applied after quality control in the data assimilation, the radiative transfer model is able to simulate the brightness temperature for all the pixels with the background and the analysis respectively for the verification purpose. The similar verification method is also applied in Yang et al., (2016)." (line 309-313).

Reference:

Yang, C., Liu, Z., Bresch, J., Rizvi, S. R. H, Huang, X.-Y., and Min, J. AMSR2 all-sky radiance assimilation and its impact on the analysis and forecast of Hurricane Sandy with a limited-area data assimilation system, Tellus A: Dynamic Meteorology and Oceanography, 68, 1,2016.

Liu, Q., and F. Weng, 2006: Advanced doubling-adding method for radiative transfer

in planetary atmosphere. J. Atmos. Sci., 63(12), 3459–3465.

We also have put the title of each figure with the band information along with the micron unit for the related figures.

Lines 300-307: I understand the authors' purpose. But these sentences should be more clarified. Without any vertical profile, it could be mere speculation. Please provide the weighting functions of each band, and it could then be discussed. And, the authors mentioned "cloud", it would be water vapors. In other words, most people may think "cloud" as "just cloud". As you know, there are many species such as ice, overwater phase, water vapor, and so on.

Reply: Agreed. The authors have plotted the weighting function for each channel in Fig. 1. Thus, the manuscript is revised as "It can be inferred from Fig. 7a, c, and e that the magnitude in OMB of channel 10 is generally larger than that of channel 9, while that of the OMB in channel 8 is the smallest. This is because the detection height of channel 10 is lower than that of channel 8 and 9 seen from the weighting function (Fig. 1), indicating channel 10 is largely affected by the clouds."

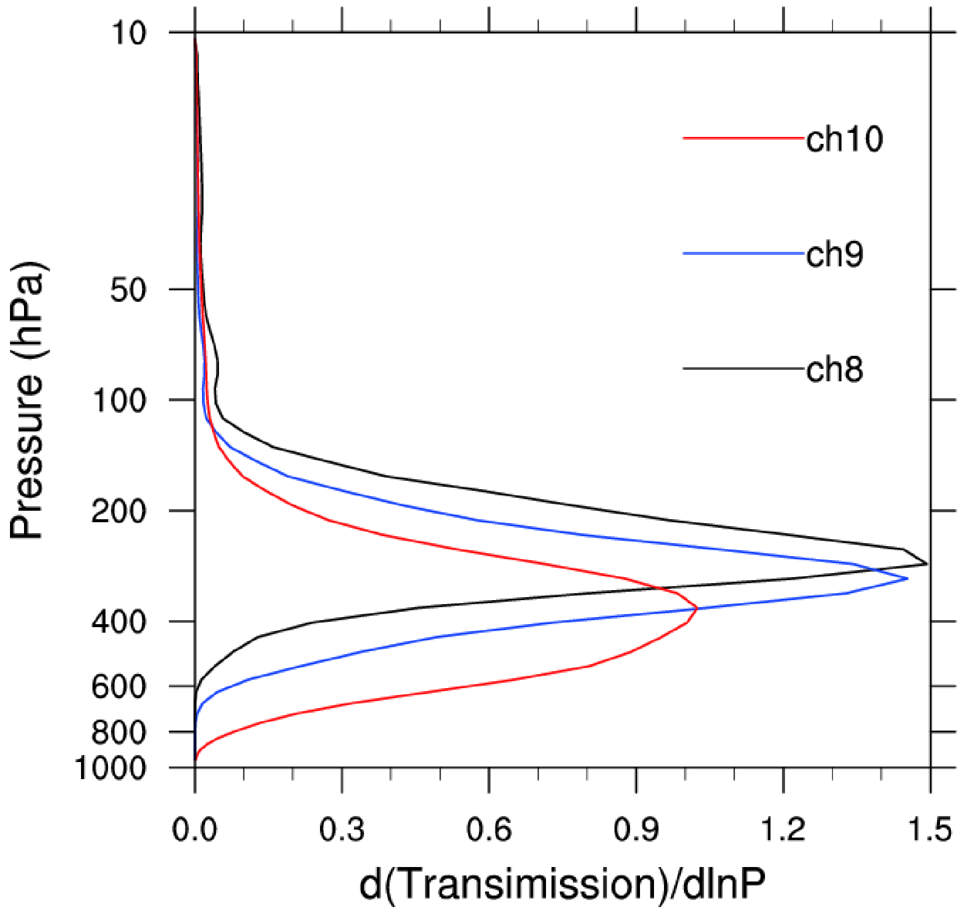


Fig.1 Weighting function for Channel 8, 9, and 10.

Figure 8: I wonder whether this stdv is statistically significant or not?

Reply: Agreed. A significance test is conducted. A sentence is added as “The pairwise significance test is made between the OMA and OMB. Results show 95% confidence intervals in terms of the difference of the standard deviation using zero difference for the null hypothesis. A sentence is added as “Differences between the standard deviations of the OMB and OMA were statistically significant at the 95% level using zero difference for the null hypothesis.”

Figure 9: I could see the improvement; however, why they fluctuate?

Reply: Fig. 9 shows the RMSEs of the simulated brightness temperature by the model before and after data assimilation against the observations. The background before the assimilation is the short-term forecast from the previous analysis. The increase of the RMSE in the fluctuation arise from the model error in the short-term forecast. To make it clear, a sentence is added as "The background before the assimilation is the short-term forecast from the previous analysis. The increase of the RMSE in the fluctuation arise from the model error in the 1 hour short-term forecast." (line377-380).

Lines 363-366: It would be better if the authors cite one reference, at least for this sentence.

Reply: Agreed. One reference is added to show the correlation between the water vapor environment and the typhoon intensity as follows,

Kamineni, R., et al., 2003: Impact of High Resolution Water Vapor Cross-Sectional Data on Hurricane Forecasting, Geophysical Research Letters, 30, 38-1.

Figure 11a: The legend is wrong. Please revise that. I guess, the figure could be enlarged.

Reply: Thanks for the helpful advice. We replotted the tracks with colorful lines in the revised manuscript. The random drawings in the background is also removed. The labeling at left is also kept. The forecast from 0000 UTC 02 August 2015 is also added for the track in Figure 12a. The forecast ranges are extended from 18 hours to 48 hours. In addition, the mean track errors, maximum surface wind speed error, and the minimum sea level pressure error are also calculated in Figure 12b, and Figure 13.

Lines: 36-39: "The predictability of these TCs is limited because it entails complex multi-scale dynamic interactions. These interactions include environmental airflows, TC vortex interactions, atmosphere-ocean interactions, and the effects of mesoscale and micro-convective scale, together with microphysics and atmospheric radiation." Is your idea? Or someone said? Please cite some works for supporting this sentence.

Reply: Corrected. The following reference is added, which describes the complex multi-scale dynamic interactions for the TCs.

Reference:

Minamide, M., and F. Zhang, 2018: Assimilation of all-sky infrared radiances from himawari-8 and impacts of moisture and hydrometer initialization on convection-permitting tropical cyclone prediction. Mon. Wea. Rev., 146, 3241–3258.

Lines 241-243: Perhaps, this sentence accounts for data assimilation, in which the observations should be independent with each other. Do the authors think a 20-km resolution is appropriate to avoid the dependency between observations? If the authors say “right”, please suggest any reference or results for that; for example, two normal distributions.

Reply: Agreed. It is proved that raw radiance observations thinned to a grid with 2–6 times of the model grid resolution are able to remove the potential error correlations between adjacent observations (Schwartz et al ., 2012; Xu et al ., 2015; Choi et al., 2017). Also, sensitivity experiments with 25 km, and 30 km thinning mesh are also conducted with similar results. Thus, the manuscript is revised as “It is proved that raw radiance observations thinned to a grid with 2–6 times of the model grid resolution are able to remove the potential error correlations between adjacent observations (Schwartz et al ., 2012; Xu et al ., 2015; Choi et al., 2017). Hence, 20 km is chosen to make thinning of AHI radiance data. Also, sensitivity experiments with 25 km, and 30 km thinning mesh are also conducted with similar results.” to make it clear.

Editorial comments

Over the whole manuscript: Please avoid to use many times “so” as the conjunction. Overall, the author should make the consistency of using the acronym and its order before the publication. For example, Lines 17-20: “The assimilation of AHI was implemented with the framework of the mesoscale numerical model WRF and its three dimensional variational assimilation system (3DVAR) for the analysis and prediction of typhoon "Soudelor" in the Pacific Typhoon season in 2015.”. Perhaps, the authors should correct some words; “AHI” ! “AHI data”; spell “WRF” out; “typhoon Soudelor” !“Typhoon Soudelor (2015)”. I guess the authors could use WRF-3DVAR “mesoscale numerical model weather research and forecasting three-dimensional variational assimilation system (WRF-3DVAR) or else. And please thoroughly see your wording to reduce mistyping or mistake since this paper goes forever after publication.

Reply: Thanks. We change “so” to other conjunctions at line 68, 73, 132, 158. Also, consistency is considered and we change the sentence from line 23 to 27. Other revisions can be found by tracks in detail.

Lines 20-21 and else somewhere: “AHI Imager data” “AHI data” since the authors already used this as the acronym above. Please correct this word in the manuscript.

Reply: Agreed. For an accurate expression, we use “AHI radiance data” in the whole manuscript.

Line 21: “. . .rapid intensify. . .” Do the authors mean “rapidly intensifying”?

Reply: Corrected. We revised it as “The effective assimilation of AHI radiance data in improving the forecast of the tropical cyclone during its rapid intensification has been realized.” at line 27-30.

Lines 20-22: This line gives me something awkward. Do you mean “the AHI data assimilation was effective to simulate rapidly intensifying TCs.”?

Reply: Corrected. This is what we mean. To avoid misunderstanding, the expression is changed to “The effective assimilation of AHI radiance data in improving the forecast of the tropical cyclone during its rapid intensification has been realized.” at line 27-30.

Line 26: forecast ! forecasts

Reply: Corrected. “forecast” is replaced with “forecasts”.

Line 35: Please use a general expression “quick intensification” ! “rapid intensification”; “exact forecast” ! “forecasts”

Reply: Thanks. The corresponding parts are corrected for the whole manuscript.

Line 40: The authors do not use the “IC” acronym after this line. Please remove this.

Reply: Thanks. “IC” acronym is removed at line 49.

Line 42: “. . .relatively limited” ! “relatively insufficient compared to the land” or proper expression.

Reply: Corrected. “relatively insufficient compared to the land” is used at line 51-52.

Line 46: “. . . now can” ! “have adopted”

Reply: Thanks for pointing it out. “have adopted” is used at line 56.

Line 47: remove “directly”

Reply: Thanks. “directly” is removed.

Lines 50-51: “improve NWP technique” ! I am not sure the authors want to say “these data improve NWP technique”? what the authors mean NWP technique? Please suggest examples.

Reply: Thanks for the helpful advice. Here we want to express abundant satellite data are crucial to the improvement of NWP accuracy because most part of the earth is covered by ocean where conventional observations are scarce. To avoid misunderstanding, “improve NWP technique” is replaced by “improve the accuracy of the numerical model results” at line 61-62.

Line 52: “. . . contributions to forecast accuracy . . .” ! “contribution to improving the accuracy of the numerical model results”, The authors should rephrase this sentence.

Reply: Thanks. The sentence is rephrased at line 63-64.

Line 58: “Besides, compared to geostationary satellites, they have higher resolutions

(Li et al., 2017; Shen et al., 2015; Xu et al., 2013)." ! "Besides, they have finer resolutions compared to geostationary satellites (Li et al., 2017; Shen et al., 2015; Xu et al., 2013).

Reply: Thanks for the helpful advice. The sentence is revised at line 69-72.

Line 61: "quickly" ! "rapidly"

Reply: Thanks. "quickly" is replaced with "rapidly" at line 74.

Line 67: "supervising" ! "observing"

Reply: Thanks. "supervising" is replaced with "observing" at line 80.

Line 126: remove "(Japan Meteorological Agency)"

Reply: Corrected. "(Japan Meteorological Agency)" is removed at line 153.

Lines 135: "satellite" ! "satellite series"

Reply: Thanks for the helpful advice. This sentence is repeated and we delete it. From line 155 to 157.

Lines 190-191: The authors need to polish this sentence.

Reply: Thanks for the helpful advice. The sentence is revised as “From the record of the China Meteorological Administration (CMA), Typhoon Soudelor was the 13th typhoon in 2015 as the second strongest tropical cyclone in that year.” at line 215.

Line 193: “west by north” ! “north-westwards”

Reply: Thanks for the helpful advice. We use “north-westwards” instead of “west by north” at line 219.

Line 205: “its main body” ! “tropical disturbance” or “tropical depression”

Reply: Thanks. “its main body” is substitute with “the tropical depression” at line 231.

Line 220: “initial condition . . .” ! “The initial condition and . . .”

Reply: Thanks for pointing it out. “The initial condition and . . .” is used at line 252.

Line 238-239: Please remove unnecessary acronyms such as “Ps”, “RHs” which words are not used anymore.

Reply: Thanks. These unnecessary acronyms are removed at line 274-275.

Line 403: 2.6 m s-1

Reply: Thanks for the helpful advice. “2.6 m s^{-1}” is used at line 437.

Assimilation of Himawari-8 Imager Radiance Data with the WRF-3DVAR system for the prediction of Typhoon Soulder

Dongmei Xu[1,2,3], Feifei Shen[1,2,3*], Jinzhong Min[1], Hong Li[4], Aiqing Shu[1]

1. The Key Laboratory of Meteorological Disaster, Ministry of Education (KLME)/Joint International Research Laboratory of Climate and Environment Change (ILCEC)/Collaborative Innovation Center on Forecast and Evaluation of Meteorological Disasters (CIC-FEMD), Nanjing University of Information Science & Technology, Nanjing 210044, China

2. Heavy Rain and Drought-Flood Disasters in Plateau and Basin Key Laboratory of Sichuan Province, Chengdu, China

3. The Institute of Atmospheric Environment, China Meteorological Administration, Shenyang 110000, China

4. Shanghai Typhoon Institute, China Meteorological Administration, Shanghai 200030, China

Abstract

Himawari-8 is a new generation geostationary meteorological satellite launched by Japan Meteorological Agency (JMA). It carries the Advanced Himawari ~~imager~~ Imager (AHI) onboard, which can continuously monitor high-impact weather events with high frequency space and time. The assimilation of AHI radiance data was implemented with the three-dimensional variational data assimilation system of ~~model~~ Weather Research and Forecasting model ~~(WRF) model and its three-dimensional variational assimilation system~~ (WRF-3DVAR) ~~system~~ for the analysis and prediction of ~~typhoon~~ Typhoon "Soudelor" (2015) in the Pacific Typhoon season ~~in 2015~~. The effective assimilation of AHI radiance ~~Imager~~ data in improving the forecast of the tropical cyclone ~~with~~ during its rapid ~~intensify~~ intensification~~development~~ has been realized. The results show that after assimilating the AHI radiance ~~imager~~ data under clear sky conditions, the typhoon position in the background field ~~in~~ of the model is effectively corrected compared with the control experiment without AHI radiance data assimilation. It is found that the assimilation of AHI radiance~~imager~~ data is able to improve the analyses of the water vapor and wind in typhoon inner-core region. The analyses and forecasts of the ~~typhoon~~ minimum sea level pressure, the maximum surface wind, and the ~~typhoon~~ track of the typhoon are further improved.

Key words: Weather Research and Forecasting model; Three-Dimensional Variational Data Assimilation; AHI Radiance~~Imager~~ Data; Typhoon

1. Introduction

In recent years, although researchers have made great progress in the field of ~~NWP (numerical~~ numerical w~~w~~eather p~~p~~rediction (NWP)~~)~~, the huge challenges are encountered in the ~~exact~~accurate forecasts of tropical cyclones (TCs) with rapid~~quick~~ intensifications (DeMaria et al., 2014). The predictability of these TCs is limited because it entails complex multi-scale dynamic interactions (Minamide and Zhang 2018). These interactions include environmental airflows, TC vortex interactions, atmosphere-ocean interactions, and the effects of mesoscale and micro-convective scale, together with the microphysics and atmospheric radiation. In order to attain a better initial condition ~~(IC)~~ and improve the accuracy of the forecast, data assimilation seeks to fully utilize the observations. ~~Most of TC's~~ The life span of most TCs is over the ocean where conventional observations are relatively insufficient compared to the land~~relatively limited~~. Therefore, by analyzing observed data from ~~the~~ satellites and planes over the ocean, it is crucial to adopt effective data assimilation (DA) methods to improve the analysis and forecast of TCs.

With the rapid development of atmospheric radiative transfer model ~~(RTM)~~, many numerical weather prediction centers have adopted~~now can adopt~~ variational DA method to assimilate a variety of radiance data from different satellite observation instruments ~~directly~~ (Bauer et al., 2011; Buehner et al., 2016; Derber et al., 1998; Hilton et al., 2009; Kazumori et al., 2014; McNally et al., 2006; Prunet et al., 2000; Pennie, 2010). These data can take up 90% of all data used in global DA system and can ~~improve the~~ improve the accuracy of the numerical model results ~~NWP accuracy technique~~ strikingly (Bauer et al., 2010). Some researches demonstrated that in global model, satellite radiance DA makes more contribution to improving the accuracy of the numerical model results~~contributions to forecast accuracy~~ than conventional observation DA does (Zapotocny et al., 2007).

Generally speaking, radiance data are~~is~~ derived from microwave and infrared detecting instruments, which are from polar-orbit satellites and geostationary satellites, respectively. Polar-orbit satellites cover the sphere of all the earth, ~~so~~thereby ~~their observations are~~ suitable for global NWP models (Jung et al., 2008). Besides, they have finer resolutions compared to geostationary satellites~~Besides, compared to geostationary satellites, they have higher resolutions~~ (Li et al., 2017; Shen et al., 2015; Xu et al., 2013). However, it is highlighted that they are not able to perform continuous monitoring over a fixed area, ~~so this can~~thus ~~leave~~ leaving out some ~~quickly~~ rapidly intensified TCs or storms. On the contrary, because geostationary satellites have a fixed location related to the earth's surface, although their resolutions are lower than that of polar-orbit satellites, they can capture the formation and development of mesoscale convective systems by continuous monitoring (Montmerle et al., 2007; Stengel et al., 2009; Zou et al.,2011).

Geostationary satellites are able to continuously detect a region at a higher frequency, thus ~~supervising~~ observing TCs over the vast ocean effectively. In fact, they can capture convective spiral cloud systems relating to TCs. ~~It is the first satellite~~

~~of all new generational geosynchronous meteorological satellites and plays a pioneering role for the geosynchronous imagers to be launched in US, China, Korea and Europe.~~As the first new generational geostationary satellite, Himawari-8 plays a pioneering role for the geosynchronous imagers to be launched in US, China, Korea and Europe~~was launched successfully in Sep 2014 by JMA (Japan Meteorological Agency) and put into operation in July 2015 (Bessho et al., 2016)~~. It has an advanced imager called ~~AHI (~~Advanced Himawari Imager (AHI)~~)~~ with 16 visible and infrared bands, including 3 moisture channels, which can conduct a full-disk scan every 10 minutes. Meanwhile, it can also acquire regional ~~scan~~scanning images and that is to say it can scan the Japan and the target areas every 2.5 minutes. Compared to the early geosynchronous imagers, AHI has more spectrum bands and this can monitor the state of atmosphere with a higher frequency.

In recent years, some experts and scholars have carried out some studies on the data assimilation of geostationary satellite observations. Firstly utilizing GSI (Gridpoint Statistical Interpolation) from NCEP (National Centers for Environmental Prediction), Zou, et al (2011) conducted direct assimilation on imagers' data from GOES-11 and GOES-12 to estimate their potential influences on QPF (quantitative precipitation forecasts) of coastal regions in the eastern part of American. They found that assimilating radiance data from GOES's imager has a remarkable improvement on 6 to 12 hour's QPF near northern Mexico Gulf coast. Their work was continued by Qin, et al (2013), which put thinned radiance data into GSI system to make a comprehensive investigation on the issue on combined assimilation of GOES Imager data together with AMSU-A (Advance Microwave Sounding Unit-A), AMSU-B (Advance Microwave Sounding Unit-B), AIRS (Atmospheric Infrared Sounder), MHS (Microwave Humidity Sounder), HIRS (High Resolution Infrared Radiation Sounder), GSN (GOES Sounder). The results showed the effect of single assimilation of AHI radiance data ~~is~~ are better than combined assimilation in term of precipitation forecast. Zou, et al (2015) adopted the GSI system to assimilate radiance data from four infrared channels on GOES-13/15 and set up two experiments for comparison. A symmetric vortex was used for initialization in the first ~~trial~~experiment and an asymmetric counterpart for the other ~~trial~~experiment. Results showed that direct assimilation of GOES-13/15's radiance data could yield positive effects on the track and intensity forecasts of hurricane "Debbie". As the new instrument of himawari-8, there are few studies on the DA of himawari-8 data. Ma, et al (2017) used 4DEnVar (four-dimensional~~4D~~ ensemble variational) DA~~data assimilation)~~ in NCEP's GSI system to assimilate radiance of three moisture channels of AHI radiance data under clear-sky condition and then NCEP GFS (Global Forecast System) was utilized to estimate the impacts of AHI radiance data assimilation on whether forecast. They found it had a positive ~~influence~~ impact on the forecast of global vapor at high level of troposphere. Wang, et al (2018) investigated the impact of assimilating ~~the~~ three water vapor channels under clear sky on the analysis and forecast of a rainstorm in Northern China ~~, based on~~with the 3DVAR method~~ in NWP center in northeast China operated by Liaoning Meteorological Bureau, firstly attempted to conduct convective~~

~~scale assimilation of AHI three moisture channels' radiance data to study its impacts on the analysis and forecast of a rainstorm in Northern China on 19th of Sep~~. It pointed out that the assimilation of AHI radiance data could improve the wind and vapor fields and the accuracy of rainfall forecast in the first 6 hours lead time.

Although ~~former~~previous researches have made several achievements in satellite data assimilation and application, it is still a challenge to make more effective use of the new generational geostationary satellite imager data with high spatial and temporal resolution. ~~so that it can better satisfy the needs of meteorology.~~ In most of the previous studies, researches usually use a 6 hour's or even longer time interval with a coarse spatial resolution. Therefore, the rapid updating assimilation techniques of the geostationary satellite radiance data have not been well carried out at convective scale. This study intends to build a data assimilation system aiming at AHI ~~imager~~ radiance data based on the new generational mesoscale Weather Research and Forecasting (WRF) model. A case of ~~typhoon~~ Typhoon Soudelor is studied by performing numerical simulation to address the impacts of convective DA on the improvement of the ~~TC's~~ initial conditions of TC and the enhancement of ~~TC's~~ track and intensity forecasts. Our study focuses mainly on assimilating the three water vapor channels (6.2, 6.9, and 7.3μm) since they are very sensitive to the humidity in the middle and upper troposphere and have a certain effect on the lower troposphere. Thus, a large amount of effective atmospheric information can be provided for AHI radiance data assimilation in the troposphere. The weighting functions for the three channels are provided in Fig. 1.

Section 2 describes the observations and the data assimilation system. Introductions to the typhoon case and the experimental setup are provided in section 3. The detailed results in terms of the analyses and the forecasts are illustrated in section 4 before conclusions are summarized in section 5.

2. Observational data and DA system

2.1 An introduction to Himawari-8 AHI radiance data

Himawari-8 satellite was launched by JMA ~~(Japan Meteorological Agency)~~ to a geosynchronous orbit on 17 October 2014 and has begun its operational use since 7 July 2015 (Bessho et al., 2016). ~~It is the first satellite of all new generational geosynchronous meteorological satellites and plays a pioneering role for the geosynchronous imagers to be launched in US, China, Korea and Europe. Himawari-8~~It is located between the equator and 140.7°E, thus~~so~~ the earth is observed between 60°N and 60°S meridionally and between 80°E and 160°W zonally. Compared to its previous generation Himawari-7, its detective ability can get significantly improved since the instrument AHI on Himawari-8. Besides, its device is comparable to imagers on American GOES-R satellite (Goodman et al., 2012; Schmit et al., 2005; Schmit et al., 2008; Schmit et al., 2017). AHI is able to provide a full-disk image every 10 minutes and complete a scan over Japan every 2.5 minutes. AHI conducts continuous scan and detection on a moving targeted typhoon. It has 16 channels covering visible, near-infrared, and infrared spectral bands with a resolution of 0.5 km or 1 km, and 2 km respectively. Channel 8 to 10 (6.2, 6.9, and 7.3 µm) are water vapor bands that are sensitive to the humidity in the middle and upper troposphere (Di et al., 2016). Other channels (channel 11, 12, 16: 8.6 µm, 9.6 µm, and 13.3µm) are either monitoring other fields such as the thin ice clouds, volcanic SO_2 gas, the ozone or CO_2, or the atmospheric window channels (13-15: 10.4, 11.2, and 12.4 µm) function as monitors for ice crystal/water, low water vapor, volcanic ash, sea surface temperature and other phenomena (Bessho et al., 2016).

~~Our work focuses mainly on assimilating the three moisture channels (6.2, 6.9, and 7.3µm) since they are very sensitive to the humidity in the middle and upper troposphere and have a certain effect on the lower troposphere. Thus, a large amount of effective atmospheric information can be provided for AHI radiance data assimilation in the troposphere.~~

2.2 WRFDA system and AHI radiance data

WRFDA system is designed by National Center for Atmospheric Research (NCAR) and it contains 3DVAR, 4DVAR, Hybrid parts. This ~~Our~~ research is based on the 3DVAR method. An interface that is suitable for AHI DA is built in WRFDA system. Currently, WRFDA is able to assimilate many conventional and unconventional observations. In terms of satellite radiance data, this system is compatible with RTTOV (the Radiative Transfer model of the Television and Infrared Observational Satellite Operational Vertical sounder) and CRTM (Community Radiative Transfer Model, Liu and Weng, 2006) as observation operators. In this study, CRTM is utilized as the observation operator to simulate and compute AHI radiance data. Estimating the systematic bias and random error of the observations caused by the errors of numerical models and instruments are the key factors to directly assimilate the satellite radiance data. Apart from eliminating cloud pixels, other procedures for quality control are as follows. (1) when reading the data, remove the observed outliers with values below 50 K or above 550 K; (2) only the marine observations are applied by removing the observations on the land and the observations over complex surfaces; (3) remove observations when the observation minus the background is larger than 3 times of the observation error; (4) the pixels are removed when the cloud liquid water path calculated by the background field of the numerical model is greater than or equal to 0.2 kg/m2; (5) eliminate the data when the observation minus background is greater than 5 K.

By using 3DVAR algorithm, the assumption is that there is no bias between observation and background (Dee et al., 2009; Liu et al., 2012; Zhu et al., 2014). A bias correction scheme for observation is essential before DA. Usually, radiance bias can be obtained by a linear combination of a set of forward operators.

$$\tilde{H}(x,\beta) = H(x) + \beta_0 + \sum_{i=1}^{N_p} \beta_i p_i \qquad (1)$$

Here, $H(x)$ represents the initial observation operator (before the bias correction), x represents the mode state vector, β_0 represents a constant component of the total bias (constant part), p_i and β_i represent the i-th predictor and its coefficient respectively. In this study, four potentially state-dependent predictors (1000–300 hPa and 200–50 hPa layer thicknesses, surface skin temperature, and total column water vapor) are applied. The variational bias correction (VarBC) scheme is utilized to update the bias correction coefficient variationally with the new observation operator considered in the cost function of 3DVAR.

3. Introduction to the ~~case~~ typhoon and experimental design

3.1 Typhoon Soudelor

From the record of the China Meteorological Administration (CMA), Typhoon Soudelor~~, that which was happened in August,~~ was the 13th typhoon in 2015 ~~and~~ as ~~became~~ the second strongest tropical cyclone in ~~this~~ that year. At 1200 UTC 30 July 2015, it formed at northwest Pacific Ocean as a tropical storm~~, located~~ at 13.6° N, 159.2° E, then moved north-westwards~~west by north~~. It upgraded to a strong tropical storm at 2100 UTC 1 August 2015. Afterwards, it went through a process of rapid intensification. It became a typhoon at 0900 UTC 2 August 2015, a strong typhoon at 2100 UTC 2 August 2015, a super typhoon at 0900 UTC 3 August 2015. Then it weakened to a strong typhoon in the morning on 5 August 2015. However, it intensified to a super typhoon again at 1200 UTC 7 August 2015 with a maximum surface wind of 52 m s^{-1}, moving west by north, and its intensity raised to its second peak. It was reduced to a strong typhoon again at 1800 UTC 7 August 2015. It decreased to a typhoon, entering to Taiwan Strait~~channel~~. It landed again as a typhoon at 1410 UTC on the coast of Fujian Province, China. Owing to continuous orographic friction, it decreased to a tropical depression. Fig. ~~1~~ 2 shows the track of Soudelor and different color lines represent typhoon's maximum surface wind. It is displayed that after the formation of typhoon, its track is relatively stable. After July 30, the tropical depression~~its main body~~ moved west by north at a speed of about 20 km/h. Its moving tendency changed slightly within 10 days of its generation. However, its intensity went through a rapid intensification, a weakening, a second intensification, then a continuous weakening till disappearing gradually after landing on the China. Fig. ~~2~~ 3 demonstrates the variation of typhoon's intensity from 31 July 2015 to 5 August 2015. It is shown that typhoon's maximum surface wind increased fast, while its minimum sea level pressure decreased sharply. This was the stage of typhoon's rapid intensification. ~~We choose t~~The date from 1 August 2015 to 3 August 2015 during its rapid intensification are selected as a ~~our~~ research object.

3.2 Experimental design

Two experiments are designed to investigate the effects of AHI radiance data direct assimilation on the analysis and forecast of Typhoon Soudelor starting from 1800 UTC 1 August 2015 to 0000 UTC 3 August 2015. WRF 3.9.1 is employed as the forecast model in this~~our~~ ~~trial~~experiment. ~~We use~~ Arakawa C grid is used in the horizon with a 5 km grid distance. As is known, Arakawa A grid is "unstaggered" by evaluating all quantities at the same point on each grid cell. The "staggered" Arakawa B-grid separates the evaluation of the velocities at the grid center and masses at grid corners. Arakawa C grid further separates evaluation of vector quantities compared to the Arakawa B-grid. Vertically, it has 41 eta levels ~~with~~ using 10 hPa as its top with coarser vertical spacing for the higher levels. Model center is (17.5 °N, 140 °E) (Fig. ~~4~~4). The initial condition and~~Initial condition and~~ lateral boundary are provided by 0.5°×0.5° Global Forecasting System (GFS) reanalysis data. The following parameterization schemes are used: The following parameterization schemes are used: WDM6 microphysics scheme (Lim et al., 2010), Grell Devenyi cumulus parameterization scheme (Grell et al., 2002), RRTM (Rapid Radiative Transfer Model) longwave radiation scheme (Mlawer et al., 1997), shortwave radiation scheme (Dudhia et al., 1989)~~WDM6 microphysics scheme (Lim et al., 2010), Grell Devenyi cumulus parameterization scheme (Grell et al., 2002), RRTM (Rapid Radiative Transfer Model) scheme (Mlawer et al., 1997) , and the Dudhia scheme (Dudhia et al., 1989) for longwave and shortwave radiation scheme (Dudhia et al., 1989) respectively~~, and YSU boundary layer scheme (~~Noh~~ Hong et al., ~~2003~~2006) ~~Noah land surface sc~~.

The experimental procedures are illustrated by Fig. ~~3~~5. Firstly, a 6 hour's spin-up conducted initialized from 1800 UTC 1 August 2015 to prepare the background field for the data assimilation at 0000 UTC 2 August 2015. The first experiment is assimilating GTS (Global Telecommunications System) conventional data (including aircraft report, ship report, sounding report, satellite cloud wind data, ground station data) only, which is called control experiment (CTNL). Another experiment is configured with AHI radiance data assimilation (AHI_DA). AHI radiance data is assimilated hourly further from 0000 UTC to 0600 UTC on 2 August 2015.

Afterwards, an ~~18~~ 48 hours forecast is launched as the deterministic forecast. The climatological background error (BE) statistics are estimated using the National Meteorological Center (NMC) method. There are 5 control variables applied in this study including U component, V component, full temperature ~~(T)~~, full surface pressure ~~(Ps)~~, and pseudo-relative humidity ~~(RHs)~~. The observation error for each channel is estimated based on the observed brightness temperature minus background brightness temperature (OMB) –from 0000 UTC on 1 August 2015 to 0000 UTC on 3 August 2015 every 6 hours.

Fig. ~~4~~ 4 ~~is~~ also shows the distribution of GTS observation data at the simulated domain at 0000 UTC 2 August 2015. It is proved that raw radiance observations thinned to a grid with 2–6 times of the model grid resolution are able to remove the potential error correlations between adjacent observations (Schwartz et al ., 2012; Xu et al ., 2015; Choi et al., 2017). Hence, 20 km is chosen to make thinning of AHI radiance data. Also, sensitivity experiments with 25 km, and 30 km thinning mesh are also conducted with similar results.~~.~~ The length scale and the variance scale are set to be 0.5 and 1 respectively after several sensitivity experiments conducted on tuning the background error. Similar conclusions are also found in Shen and Min (2015) with the scale factors related to the static background error covariance.

4. Results

4.1 Minimization iterations

Fig. ~~5~~ 6 shows the cost function and gradient with the iteration times. There is an obvious exponential decrease curve in Fig. ~~5a~~6a, while Fig. ~~5b~~ 6b shows gradient decreases with the increase of iteration times. Taking Fig. ~~5a~~ 6a as an example, cost function decreases remarkably in the first 10 iterations. However, after 30 times of iteration, the cost function curve becomes smooth gradually. The differences between background field and observation are largest. With continuous iterations, background field goes through continued adjustments. Finally, the cost function tends to reach a stable minimum that represents the point when cost function has its optimal solution. Besides, the gradient in Fig. ~~5b~~ 6b decreases stably with increasing iterations. The exponential decrease of the cost function and the change trend of its gradient indicate that the effectiveness of AHI radiance DA. The final iterated analytical field is close to the observation.

4.2 Analytical results of the brightness temperature

Fig. ~~6~~7a, c, e show~~s~~ the distribution of OMB ~~and~~, while the observed brightness temperature minus analytical brightness temperature (OMA) after the bias correction of AHI radiance data are presented in Fig. 7b, d, f from channel 8, 9, and 10 at 0000 UTC 2 August 2015. It should be pointed that even only parts of the AHI radiance data are applied after quality control in the data assimilation, the radiative transfer model is able to simulate the brightness temperature for all the pixels with the background and the analysis respectively for the verification purpose. The similar verification method is also applied in Yang et al., (2016). ~~Fig. 6a is shows the distribution of OMB brightness temperature after the bias correction.~~ In the ~~figure~~Fig. 7a, part of typhoon’s spiral cloud belt is clearly visible. The brightness temperature in typhoon’s inner-core area is low, while the brightness temperature in other areas is high. The mean of observed OMB was -4.65 K, indicating that the background brightness temperature is higher than the observation. It is found in Fig. ~~6b~~ 7b ~~shows~~ that the OMA values of most pixels are below 0.02 K, indicating that the analytical field fitting the observation after analyzing. It can be inferred from Fig. ~~6a~~7a, c, and e that the magnitude in OMB of channel 10 is generally larger than that of channel 9, while that of the OMB ~~of~~ in channel 8 is the smallest. This is because the detection height of channel 10 is lower than that of channel 8 and 9 seen from the weighting function (Fig. 1~~Wang et al., 2018~~), ~~which is~~indicating channel 10 is largely affected by the clouds. ~~.~~ Conversely, the weighting peak of the channel 8 is the highest, being least affected by the clouds. ~~.~~In general, the analytical brightness temperature match well with the observed brightness temperature of all the three water vapor channels after the assimilation of AHI radiance data.

Fig. ~~7~~ 8 ~~illustrates~~ shows the effect of the bias correction for AHI radiance data at 0000 UTC 2 August 2015. Fig. ~~7a~~8a, d, g ~~are~~ show the scatter plots of the observed brightness temperature and the brightness temperature from the background before the bias correction. Fig. ~~7b~~8b, e, h ~~are~~ show results after bias correction. Fig. ~~7c~~8c, f, i ~~are~~ show the scatter plots of observed brightness temperature and analytical brightness temperature after bias correction. From Fig. ~~7a~~8a, before the bias correction, the values from the observation and the background are ~~compariable~~comparable, but most of the scatter points are below the diagonal line. This suggests that the observed brightness temperature is higher than the background simulated brightness temperature. From Fig. ~~7b~~8b, after the bias correction, observed warm bias is corrected to some extent. From Fig. ~~7a~~8a, b, after the bias correction, the root mean square error (RMSE) of OMB decreases from 1.864 K to 1.627 K, with the average decreasing from 0.956 K to 0.358 K, proving the validity and rationality of the variational bias correction. Compared to the result of Fig. ~~7b~~8b, the scatters in Fig. ~~7c~~ 8c are more symmetrical, fitting closely to the diagonal line. The mean and RMSE were also significantly reduced, suggesting that the analytical field is more similar to observation than background field. Channel 9, 10 have a similar result, but with a significantly reduced mean and RMSE, indicating that the background field and analytical field of channel 9, 10 match better with the observation than channel 8 does. Among them the RMSE of channel 10 ~~reaches the minimum~~is smallest as 0.234 K in Fig. 8i, which is likely related to strict cloud detection scheme for channel 10 with rather lower detecting peak (Wang et al., 2018). ~~. In Fig. 7i, the RMSE of channel 10 analytical field is only 0.234 K.~~

Fig. ~~8~~ 9 shows the observation numbers, the mean, and the standard deviation of OMB and OMA of channel 8, 9, and 10 before and after the bias correction. It can be seen that after the quality control, 24057, 24181, 21785 observations are adopted in the DA system for channel 8, 9, and 10, respectively. From the mean value of OMB before the bias correction, the value of the three channels is relatively small, indicating that the simulated brightness temperature of the three channels is close to the observed brightness temperature. The lowest mean of 0.3 K is found in channel 10, indicating that the simulated brightness temperature of channel 10 is closest to the observed brightness temperature. Bias correction effectively corrects the systematic bias and reduces the mean value of observation residuals. After the bias correction, the OMB mean value of the three channels significantly decreases to nearly 0 K. With the bias correction, the simulated brightness temperature is almost the same as the observed brightness temperature. The analysis of the standard deviation of OMB shows that the results are comparable before and after the bias correction. The standard deviation of OMA decreases by about 80% compared to OMB, indicating that the analyses fit better with the observations after the data assimilation. Differences between the standard deviations of the OMB and OMA were statistically significant at the 95% level using zero difference for the null hypothesis.

The RMSEs of the simulated brightness temperature by the NWP model before and after the assimilation ~~and assimilation against the observation~~ ~~is~~ are also calculated against the AHI radiance observations. Fig. ~~9~~ 10 shows the RMSEs during the DA cycles for channels 8, 9, 10. As can be seen from Fig. ~~9~~10, RMSE decreases after each analysis in AHI_DA. The most significant improvement is from the first analysis cycle of channel 8, where RMSE of the brightness temperature after assimilation significantly decreases from 1.64 K to 0.46 K, possibly due to the largest adjustment on the background for the first analysis time. The background before the assimilation is the short-term forecast from the previous analysis. The increase of the RMSE in the fluctuation arise from the model error in the 1 hour short-term forecast.~~The one hour forecast after the analysis basically makes brightness temperature of RMSE increase.~~ Overall, the effect of the analysis from the channel 10 is most significant.

4.3 Analysis of the typhoon structure

Fig. ~~10~~ 11 shows the wind field at sea level and the distribution of water vapor at 850 hPa at 0000 UTC 2 August 2015. The obvious cyclonic eddy circulation structures in the core area of the typhoon are found in both fields, while the anti-cyclonic circulation exists in the northwest quadrant of the typhoon. The mixing ratio of water vapor in the region where the typhoon ~~is~~ located is very high and the wind field is cyclonic, indicating that the typhoon has a continuous water vapor advection. This contributes to the enhancement of typhoon (Kamineni, et al., 2003). ~~According to~~From the flow field of the control experiment in Fig. ~~10a~~11a, the water vapor convergence in the center of the typhoon region is weak with the low intensity and smaller coverage. As can be seen from Fig. ~~10b~~11b, after the assimilation of AHI radiance data, the streamlines in the typhoon region become denser, indicating that the cyclonic circulation is strengthened. Conversely, the intensity and distribution of the water vapor after the assimilation of AHI radiance data tend to contribute to the developing typhoon. This suggests that the assimilation of AHI radiance data ~~is~~ are able to significantly improve the large-scale environmental field in the simulation region of Typhoon Soudelor. It should be pointed out that the model status in the cloudy area are modified due to the spatial correlation in the background error covariance. The similar findings for small-scale information in the cloudy area can also be referred in Wang et al., (2018).

4.4 Track forecast

In order to further evaluate the effect of AHI radiance data assimilation, ~~a~~ a ~~18~~48-hour deterministic forecast ~~is~~ is launched ~~at the end of~~with the analyses ~~two assimilation experiments~~initialized from 0000 UTC 2 August 2015 and 0600 UTC 2 August 2015 respectively. The best track data are provided by the CMA (Yu et al., 2007; Song et al., 2010)~~The typhoon best track data are from the CMA.~~ As can be seen in Fig. ~~11a~~12a, at the beginning of the forecast, the initial location of the typhoon from the ~~two trials~~CTNL experiment has ~~a~~ large south bias and east bias at 0000 UTC and 0600 UTC respectively. ~~The location of the typhoon in the control experiment has a relative east-southward bias, while~~Conversely, the location of the typhoon in AHI_DA is relatively closer to the observation at the beginning. During the following ~~6~~ few hours of ~~–~~ forecasts, the typhoon track predicted by the CTNL continues ~~moving west-south~~to show a south-west bias with the environmental wind, while the track predicted by AHI_DA match better with the best track ~~track than that of the CTNL~~. ~~In summary, the track of AHI_DA trial is closest to the observation track~~

~~during the entire 18-hour deterministic forecast.~~ Fig. ~~11b~~ 12c ~~is~~ shows the averaged typhoon track error over the two forecasts predicted by the two experiments. At the initial time of the forecast, the track errors of CTNL and AHI_DA are significantly different, with the magnitude of ~~63~~55.~~2km~~ 6 km and ~~16~~13.~~7km~~4 km, respectively. During the subsequent ~~18~~48-hour forecast, the track error of the CTNL gradually increases with the forecast time reaching ~~232~~167.~~5km~~ 1 km at the end of the forecast. In contrast, the track error of AHI_DA is consistently less than ~~95~~ 122.5 km during the ~~18~~48-hour forecast period. In general, the average track error of the CTNL is ~~123~~168.~~46~~ 57 km, and the average track error of AHI_DA experiment is only ~~53~~ 67.0 km, indicating a significant improvement in the track prediction.

Fig. ~~12~~ 13 ~~discusses~~ provides the time series of the typhoon intensity from the two experiments ~~with~~ in terms of the averaged maximum surface wind and minimum sea level pressure ~~shown in Fig. 12a and Fig. 12b respectively~~error over the two forecasts initialized from 0000 UTC 2 August 2015 and 0600 UTC 2 August 2015 respectively. It can be seen that the maximum surface wind error predicted by the AHI_DA ~~CTNL~~ is much lower than that by the CTNL~~actual wind speed~~, ~~mainly because~~due to the overall under estimation for the strength of Typhoon Soudelor simulated in the background field~~ of the model is relatively weaker~~. The maximum surface wind predicted by AHI_DA fit closer to the best track data ~~–~~with the maximum difference about 2.6 m s^{-1}~~.6m /s~~ after 12 hours forecast~~.~~ ~~In,~~. In Fig. ~~12b~~13b, the results of the minimum sea level pressure are consistent with Fig. ~~12a~~13a.

5. Conclusion

An interface for AHI radiance data assimilation on the WRFDA system based on the 3DVAR assimilation method was built. Based on the Typhoon Soudelor in 2015, two experiments for comparison was designed to examine the impact of AHI water vapor channel radiance data assimilation on the analysis and prediction of the rapid development stage of Typhoon Soudelor under clear sky condition. Following conclusions are obtained:

(1) The AHI radiance data ~~imager~~ on the new generation of geostationary meteorological satellite is able to reflect the structure of Typhoon Soudelor very clearly. After a series of pre-procedures such as the quality control, the bias correction, cloudy pixels are able to effectively be eliminated, ensuring the validity and rationality of the Ahi radiance data. The biases are also eliminated from the VarBC statistical method, which is able to provide a positive impact on the data assimilation procedure for the typhoon numerical simulation.

(2) Compared with the control experiment with only GTS data, the 3DVAR assimilation including AHI radiance data is able to improve the structure of typhoon's core and outer rain band. Also, the position and intensity of typhoon in the background field are able to be corrected.

(3) It is found that the track, maximum surface wind, and minimum sea level pressure from the AHI radiance data assimilation experiment match better with the best track than the control experiment does for the subsequent 18-hour forecast.

In t~~T~~his ~~manuscript paper realizes~~ study, the AHI water radiance data assimilation is conducted under the clear sky condition. The results of the experiments indicate that AHI radiance data assimilation has a positive effect on the analysis and prediction of rapidly intensifying TC. Considering the complex influence of underlying surface, only the rapid development stage of typhoon at sea were studied, while the whole generation, development and disappearance stage of typhoon can also be studied in the future. In addition, based on the AHI radiance data of the water vapor channels under the condition of clear sky, only 3DVAR method was adopted. Further improvements under the condition of all sky and hybrid DA can be obtained in the future.

Acknowledgments

This research was primarily supported by the Chinese National Natural Science Foundation of China (G41805016), the Natural Science Foundation of Jiangsu Province (BK20170940), the Chinese National Natural Science Foundation of China (G41805070), the Chinese National Key R&D Program of China (2018YFC1506404, 2018YFC1506603), the research project of Heavy Rain and Drought-Flood Disasters in Plateau and Basin Key Laboratory of Sichuan Province in China (SZKT201901, SZKT201904), the research project of the Institute of Atmospheric Environment, China Meteorological Administration, Shenyang in China (2020SYIAE07, 2020SYIAE02).

References

Bauer, P., Geer, A.J., Lopez, P., and Salmond, D.: Direct 4D–Var assimilation of all-sky radiance. Part I: Implementation, Quarterly Journal of the Royal Meteorological Society, 136, 1868-1885, 2010.

Bauer, P., Auligné, T., Bell, W., Geer, A., Guidard, V., Heilliette, S., et al: Satellite cloud and precipitation assimilation at operational NWP centres, Quarterly Journal of the Royal Meteorological Society, 137, 1934-1951, 2011.

Bessho, K., Date, K., Hayashi, M., Ikeda, A., Imai, T., Inoue, H., et al.: An introduction to Himawari-8/9—Japan's new-generation geostationary meteorological satellites, Journal of the Meteorological Society of Japan, 94, 151-183, 2016.

Buehner, M., Caya, A., Carrieres, T., and Pogson, L.: Assimilation of SSMIS and ASCAT data and the replacement of highly uncertain estimates in the Environment Canada Regional Ice Prediction System, Quarterly Journal of the Royal Meteorological Society, 142, 562-573, 2016.

Choi, Y., Cha, D.-H., Lee, M.-I., Kim, J., Jin, C.-S., Park, S.-H., and Joh, M.-S.: Satellite radiance data assimilation for binary tropical cyclone cases over the western North Pacific, J. Adv. Model. Earth Syst., 9, 832-853, 2017.

Dee, D.P., and Uppala, S.: Variational bias correction of satellite radiance data in the ERA–Interim reanalysis, Quarterly Journal of the Royal Meteorological Society, 135, 1830-1841, 2009.

DeMaria, M., Sampson C.R., Knaff J.A., and Musgrave K.D.: Is tropical cyclone intensity guidance improving? Bulletin of the American Meteorological Society, 95, 387-398, 2014.

Derber, J.C., and Wu, W.S.: The use of TOVS cloud–cleared radiance in the NCEP SSI analysis system, Mon. Wea. Rev, 126, 2287-2299, 1998.

Di, D., Ai, Y., Li， J., Shi, W., and Lu, N.: Geostationary satellite-based 6.7 μm band best water vapor information layer analysis over the Tibetan Plateau, Journal of Geophysical Research: Atmospheres, 121, 4600-4613, 2016.

Dudhia, J.: Numerical Study of Convection Observed during the Winter Monsoon Experiment Using a Mesoscale Two-Dimensional Model, Journal of the Atmospheric Sciences, 46, 3077-3107, 1989.

Goodman, S.J., Gurka, J., DeMaria, M., Schmit, T.J., Mostek, A., Jedlovec, G., et al.: The GOES-R proving ground: Accelerating user readiness for the next-generation geostationary environmental satellite system, Bulletin of the American Meteorological Society, 93, 1029-1040, 2012.

Grell G.A., Dévényi D.: A generalized approach to parameterizing convection combining ensemble and data assimilation techniques, Geophys. Res. Let., 29, 587-590, 2002.

Hilton, F., Atkinson, N. C., English, S. J., and Eyre, J. R.: Assimilation of IASI at the Met Office and assessment of its impact through observing system experiments, Quarterly Journal of the Royal Meteorological Society, 135, 495-505, 2009.

Hong S.Y., Noh Y., Dudhia J.: A New Vertical Diffusion Package with an Explicit Treatment of Entrainment Processes. Mon. Wea. Rev, 134, 2318-2341, 2006.

Jung, J.A., Zapotocny, T.H., Le Marshall, J.F., and Treadon, R.E.: A two-season impact study on NOAA polar-orbiting satellites in the NCEP Global Data Assimilation System, Weather Forecasting, 23, 854-877, 2008.

Kamineni, R., Krishnamurti, T., Ferrare, R., Ismail, S., and Browell, E.: Impact of high resolution water vapor cross-sectional data on hurricane forecasting, Geophysical Research Letters, 30, 38-1, 2003.

Kazumori, M.: Satellite radiance assimilation in the JMA operational mesoscale 4DVAR system, Mon. Wea. Rev, 142, 1361-1381, 2014.

Li, X., and Zou, X.: Bias characterization of CrIS radiances at 399 selected channels with respect to NWP model simulations, Atmospheric Research, 196, 164-181, 2017.

Lim, K.-S. S., and Hong, S.-Y.: Development of an effective double-moment cloud microphysics scheme with prognostic cloud condensation nuclei (CCN) for weather and climate models. Mon. Wea. Rev, 138, 1587-1612, 2010.

Liu, Z., Schwartz, C.S., Snyder, C., and Ha, S.Y.: Impact of assimilating AMSU-A radiance on forecasts of 2008 Atlantic tropical cyclones initialized with a limited-area ensemble Kalman filter, Mon. Wea. Rev,~~Monthly Weather Review~~, 140, 4017-4034, 2012.

Liu, Q., and Weng, F.: Advanced doubling-adding method for radiative transfer in planetary atmosphere. J. Atmos. Sci., 63, 3459–3465, 2006.

Ma, Z., Maddy E.S., Zhang B., Zhu T., and Boukabara S.A.: Impact Assessment of Himawari-8 AHI Data Assimilation in NCEP GDAS/GFS with GSI, J. Atmos. Oceanic Technol., 34, 797-815, 2017.

McNally, A.P., Watts, P.D., Smith, J.A., Engelen, R., Kelly, G.A., Thépaut, J.N., and Matricardi, M.: The assimilation of AIRS radiance data at ECMWF, Quarterly Journal of the Royal Meteorological Society, 132, 935-957, 2006.

Minamide, M., and Zhang F.: Assimilation of all-sky infrared radiances from himawari-8 and impacts of moisture and hydrometer initialization on convection-permitting tropical cyclone prediction. Mon. Wea. Rev, 146, 3241-3258, 2018.

Mlawer E.J., Taubman S.J., Brown P.D., et al.: Radiative transfer for inhomogeneous atmospheres: RRTM, a validated correlated-k model for the longwave, Journal of Geophysical Research Atmospheres, 102, 16663-16682, 1997.

Montmerle, T., Rabier, F., and Fischer, C.: Relative impact of polar–orbiting and geostationary satellite radiance in the Aladin/France numerical weather prediction system, Quarterly Journal of the Royal Meteorological Society, 133, 655-671, 2007.

Noh Y., Cheon W.G., Hong S.Y., et al.: Improvement of the K-profile Model for the Planetary Boundary Layer based on Large Eddy Simulation Data, Boundary-Layer

Meteorology, 107, 401-427, 2003.

Prunet, P., Thépaut, J.N., Cassé, V., Pailleux, J., Baverez, A., and Cardinali, C.: Strategies for the assimilation of new satellite measurements at Météo–France, Advances in Space Research, 25, 1073-1076, 2000.

Qin, Z., Zou, X., Weng, F.: Evaluating Added Benefits of Assimilating GOES Imager Radiance Data in GSI for Coastal QPFs, Mon. Wea. Rev, 141, 75-92, 2013.

Rennie, M.P.: The impact of GPS radio occultation assimilation at the Met Office, Quarterly Journal of the Royal Meteorological Society, 136, 116-131, 2010.

Schmit, T.J., Gunshor, M.M., Paul Menzel, W., Gurka, J., Li, J., and Bachmeier, S.: Introducing the next–generation advanced baseline imager (ABI) on GOES-R, Bulletin of the American Meteorological Society, 86, 1079-1096, 2005.

Schmit, T.J., Li, J., Li, J., Feltz, W.F., Gurka, J.J., Goldberg, M.D., and Schrab, K.J.: The GOES-R Advanced Baseline Imager and the continuation of current sounder products, Journal of Applied Meteorology and Climatology, 47, 2696-2711, 2008.

Schmit, T.J., Griffith, P., Gunshor, M.M., Daniels, J.M., Goodman, S.J., and Lebair, W.J.: A closer look at the ABI on the GOES-R series, Bulletin of the American Meteorological Society, 98, 681-698, 2017.

Schwartz, C. S., Liu, Z., Chen, Y. and Huang X. - Y.: Impact of assimilating microwave radiances with a limited - area ensemble data assimilation system on forecasts of Typhoon Morakot, Weather Forecasting, 27, 424-437, 2012.

Shen, F., and Min, J.: Assimilating AMSU-A radiance data with the WRF hybrid En3DVAR system for track predictions of Typhoon Megi (2010), Advances in Atmospheric Sciences, 32, 1231-1243, 2015.

Song J-J, Wang Y, Wu L.: Trend discrepancies among three best track data sets of western North Pacific tropical cyclones. J. Geophys. Res. 115: D12128, DOI: 10.1029/2009JD013058, 2010.

Stengel, M., Undén, P., Lindskog, M., Dahlgren, P., Gustafsson, N., and Bennartz, R.: Assimilation of SEVIRI infrared radiance with HIRLAM 4D-Var, Quarterly Journal of the Royal Meteorological Society, 135, 2100-2109, 2009.

Wang, Y., Liu, Z., Yang, S., Min, J., Chen, L., Chen, Y., and Zhang, T.: Added value of assimilating Himawari-8 AHI water vapor radiances on analyses and forecasts for “7.19” severe storm over north China, Journal of Geophysical Research: Atmospheres, 123, 3374-3394, 2018.

Xu, D., Liu, Z., Huang, X.-Y., Min, J., and Wang, H.: Impact of assimilation IASI radiances on forecasts of two tropical cyclones, Meteorology and Atmospheric Physics, 122, 1-18, 2013.

Xu, D., Huang X.-Y., Wang H., Mizzi, A. P. and Min J.: Impact of assimilating radiances with the WRFDA ETKF/3DVAR hybrid system on prediction of two typhoons in 2012, J. Meteorol. Res, 29, 28-40, 2015.

Yang, C., Liu, Z., Bresch, J., Rizvi, S. R. H, Huang, X.-Y., and Min, J.: AMSR2 all-sky radiance assimilation and its impact on the analysis and forecast of Hurricane Sandy with a limited-area data assimilation system, Tellus A: Dynamic Meteorology and Oceanography, 68, 2016.

Yu H, Hu C, Jiang L.: Comparison of three tropical cyclone intensity datasets. Acta Meteorol. Sin. 21, 121-128, 2007.

Zapotocny, T.H., Jung, J.A., Le Marshall, J.F., and Treadon, R.E.: A two–season impact study of satellite and in situ data in the NCEP Global Data Assimilation System, Weather Forecasting, 22, 887-909, 2007.

Zhu, Y., Derber, J., Collard, A., Dee, D., Treadon, R., Gayno, G., and Jung, J.A.: Enhanced radiance bias correction in the National Centers for Environmental Prediction's Gridpoint Statistical Interpolation data assimilation system, Quarterly Journal of the Royal Meteorological Societ, 140, 1479-1492, 2014.

Zou, X., Qin, Z., and Weng, F.: Improved coastal precipitation forecasts with direct assimilation of GOES-11/12 imager radiance, Mon. Wea. Rev, 139, 3711-3729, 2011.

Zou, X., Qin Z., and Zheng Y.: Improved tropical storm forecasts with GOES-13/15 imager radiance assimilation and asymmetric vortex initialization in HWRF, Mon. Wea. Rev, 143, 2485-2505, 2015.

List of Figures

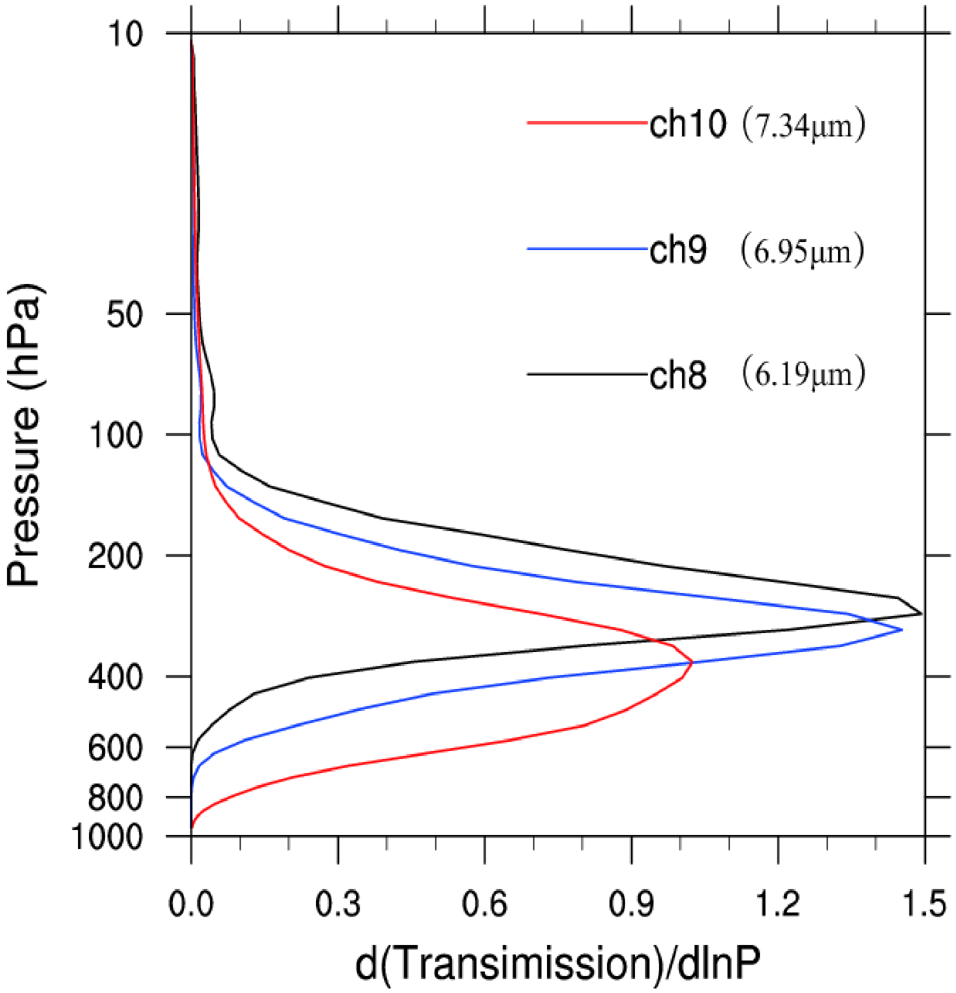


Fig.1 Weighting functions of Himawari-8 Advanced Himawari Imager three water vapor channels for Channel 8, 9, and 10.

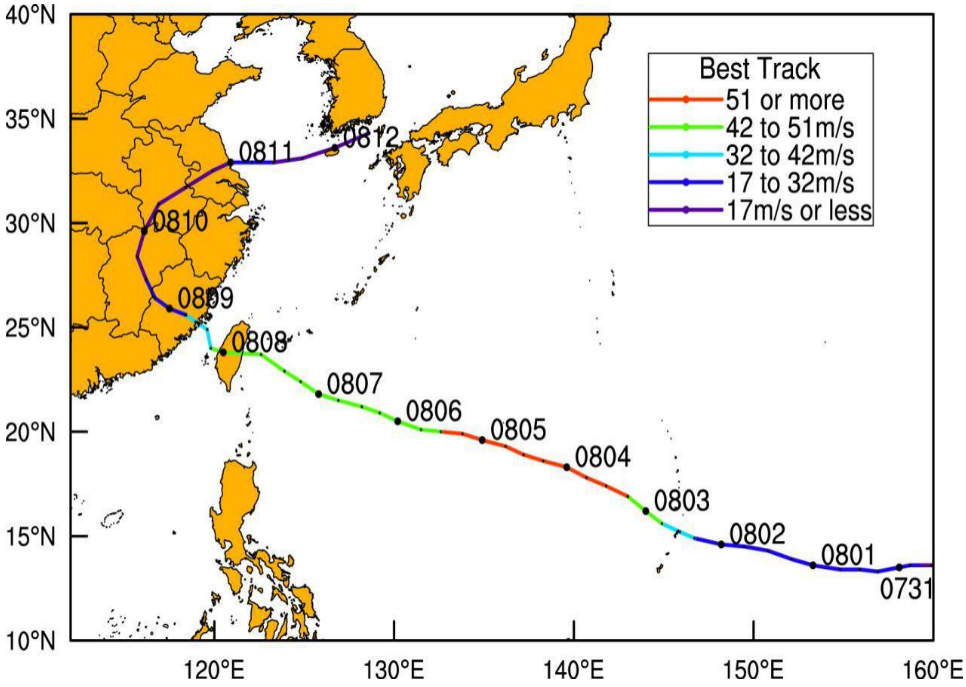
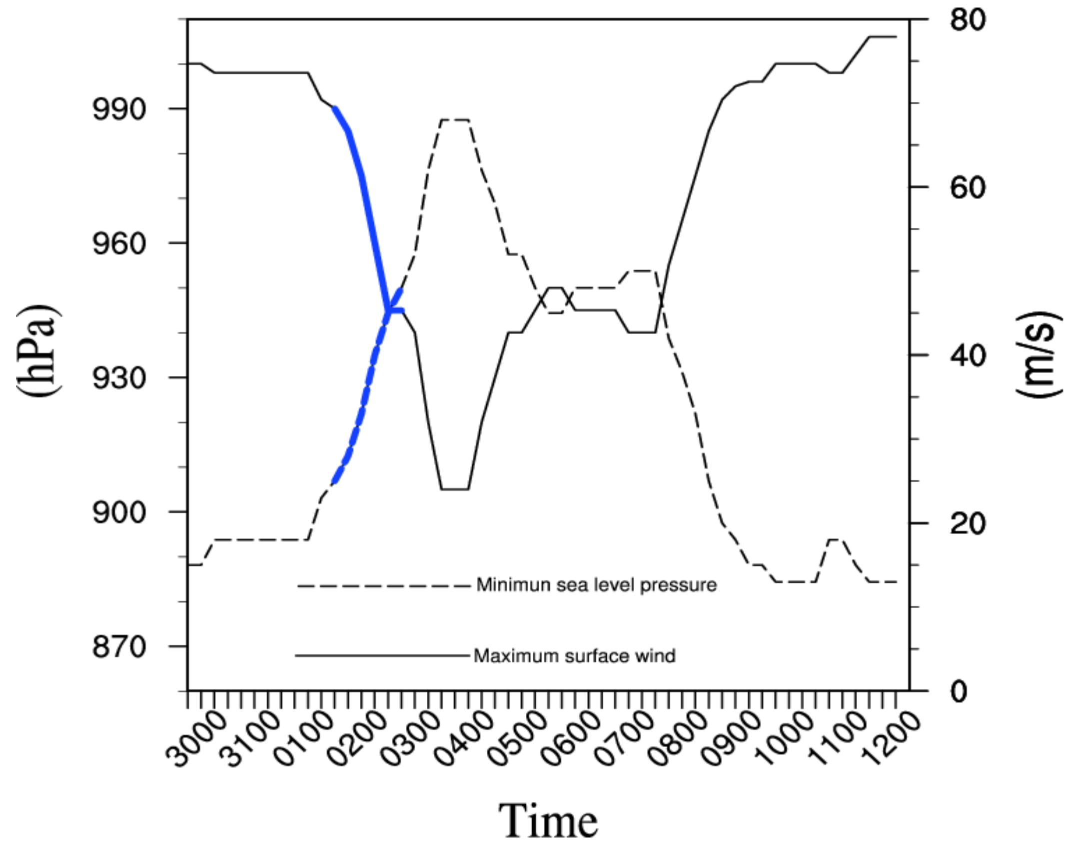


Fig.~~1~~ 2 The best track of Soudelor from the China Meteorological Administration (CMA) from 0000 UTC 30 July to 0600 UTC 12~~in~~ August~~–~~ 2015. Different colors represent intensity changes.



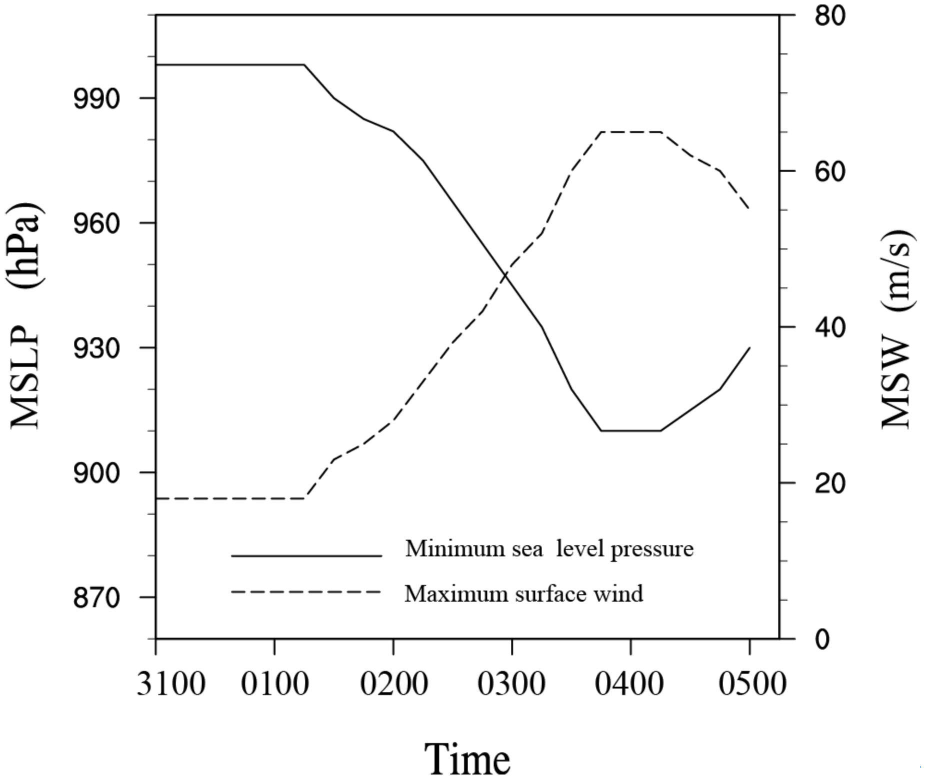


Fig. ~~2~~ 3 The time series of the minimum sea level pressure (solid line, unit: hPa) and the maximum surface wind (dash line, unit: m s-1) of typhoon Soudelor from the CMA best-track data.

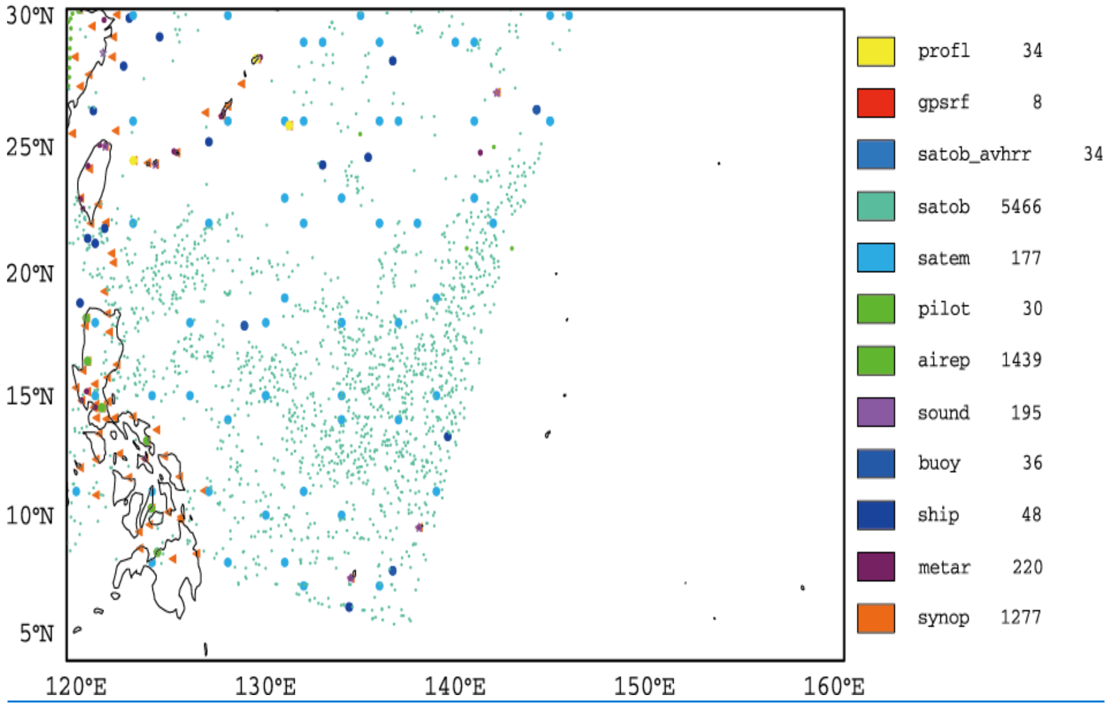


Fig. 4 Distribution of GTS observations in the simulated area at 0000 UTC 2 August 2015. On the right side of the map is the name of observation data and the number of

observations.

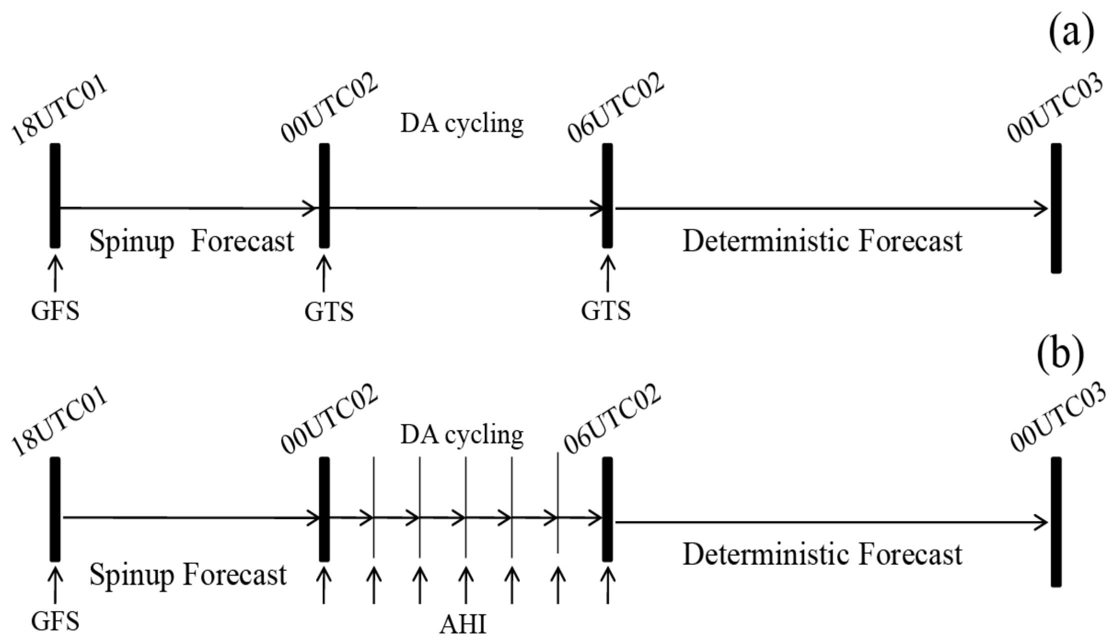
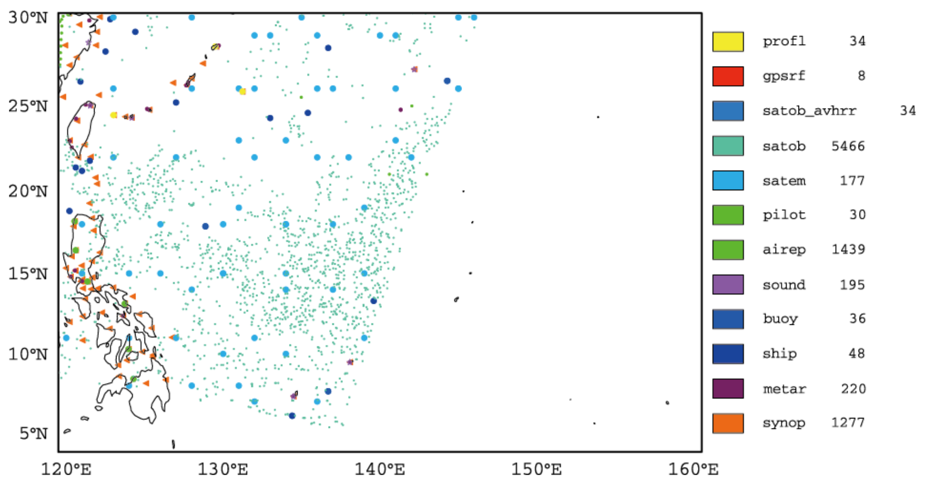


Fig. ~~3~~ 5 The flow chart of the data assimilation experiments. (a) CTNL, (b) AHI_DA



~~Fig. 4 Distribution of GTS in the simulated area at 0000 UTC 2 August 2015. On the~~

~~right side of the map is the name of observation data and the number of observations.~~

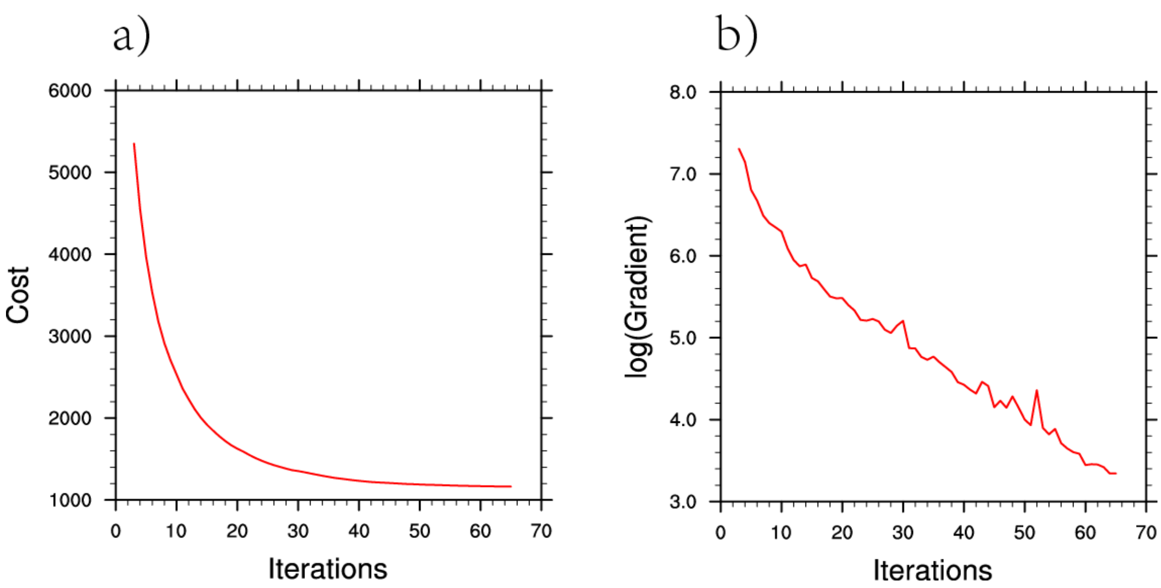


Fig. ~~5~~ 6 (a) Cost function as functions of iterations, (b) gradient as functions of iterations.

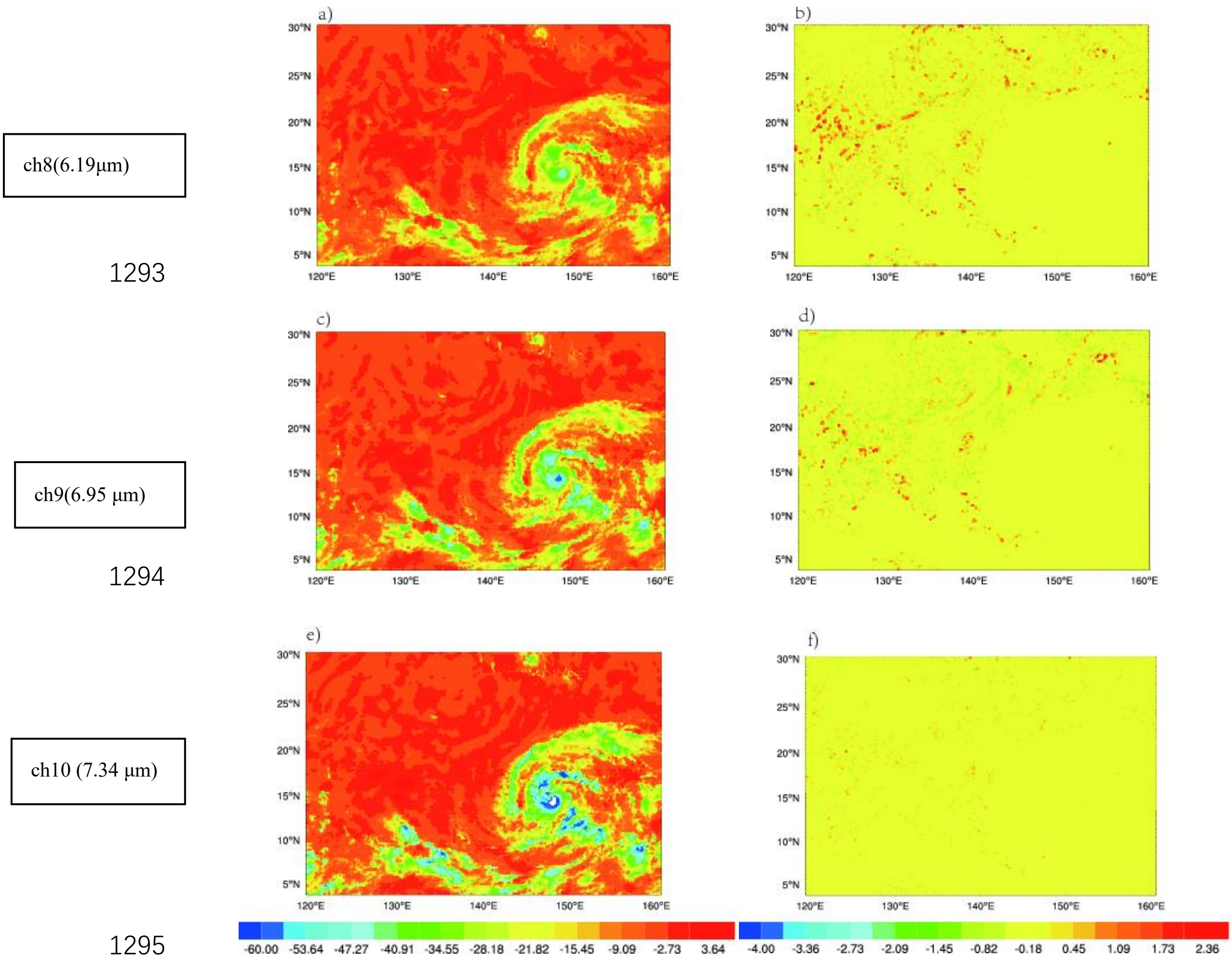


Fig. 7 (a, c, and e) OMB (unit: K) after bias correction for channel 8, 9, and 10, respectively; (b, d, and f) OMA (unit: K) after bias correction for channel 8, 9, and 10, respectively at 0000 UTC 2 August 2015.

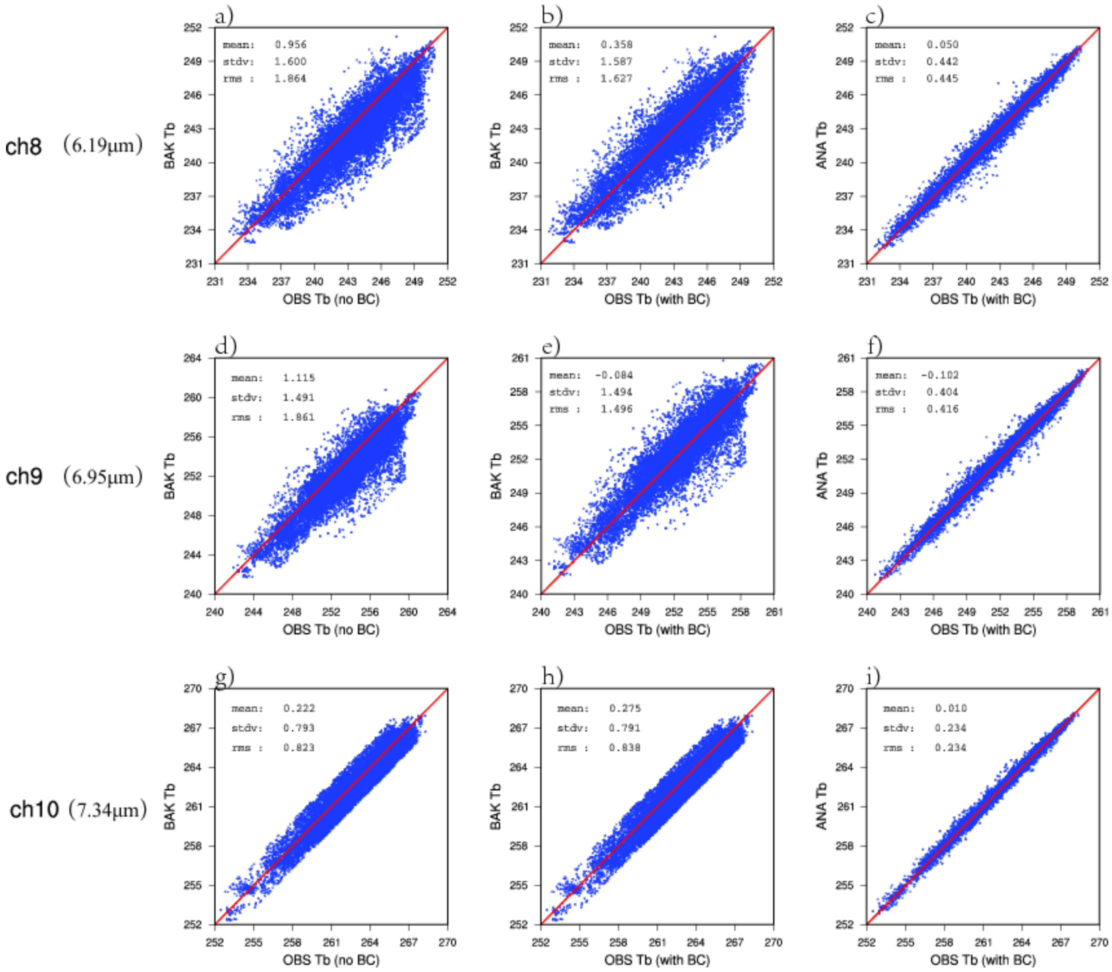


Fig. ~~7~~ 8 Scatter plots of (a, d and g) the observed and background brightness temperature before the bias correction of channel 8, 9 and 10. Scatter plots of (b, e and h) the observed and background brightness temperature after the bias correction of channel 8, 9 and 10. Scatter plots of (c, f and i) the observed and analyzed brightness temperature after the bias correction of channel 8, 9 and 10.

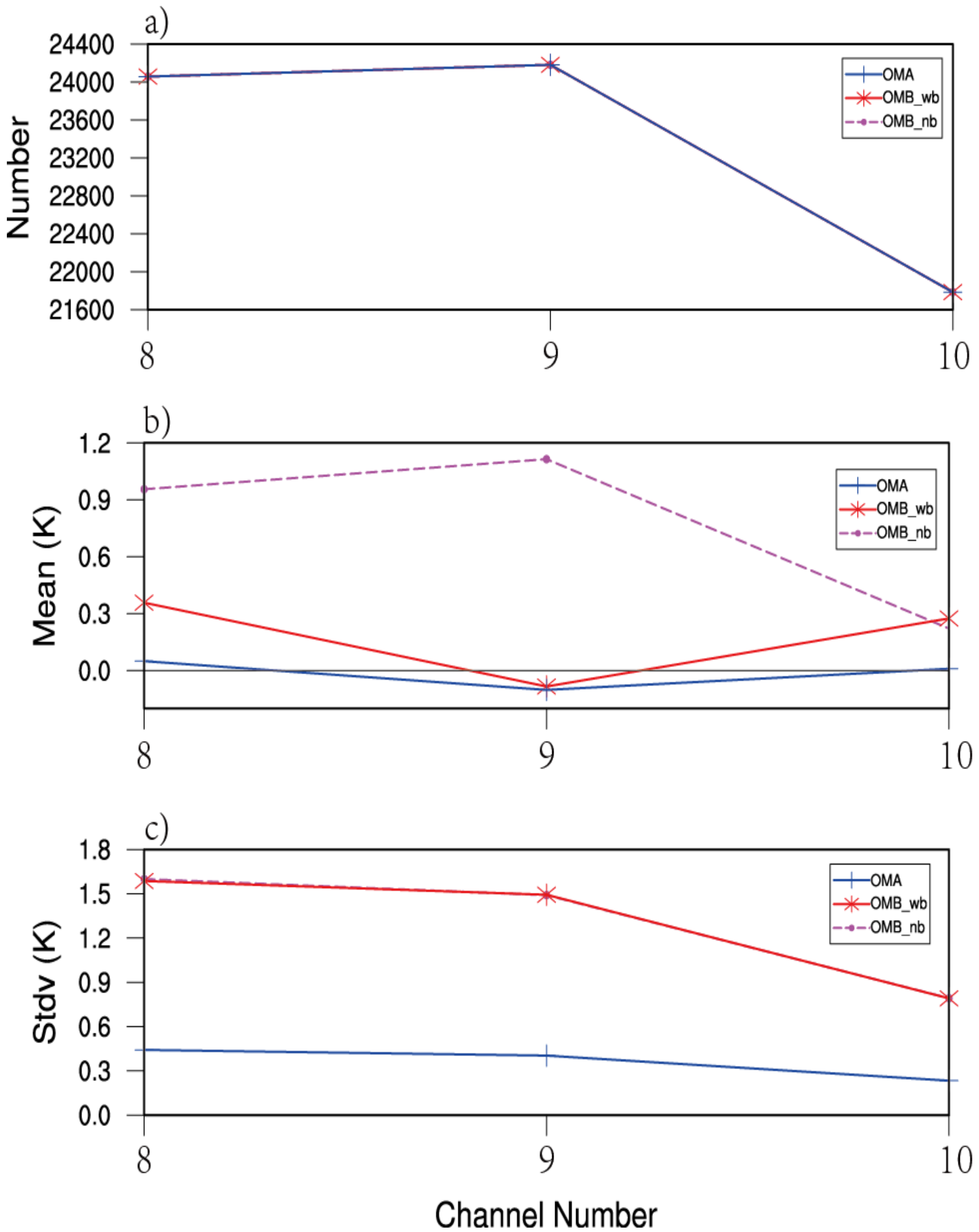


Fig. ~~8~~ 9 Number of (a) observations, (b) mean (unit: K), and (c) standard deviations (unit: K) of OMB and OMA before and after the bias correction for water vapor channels 8-10 (OMB_nb: OMB without bias correction; OMB_wb: OMB with bias correction).

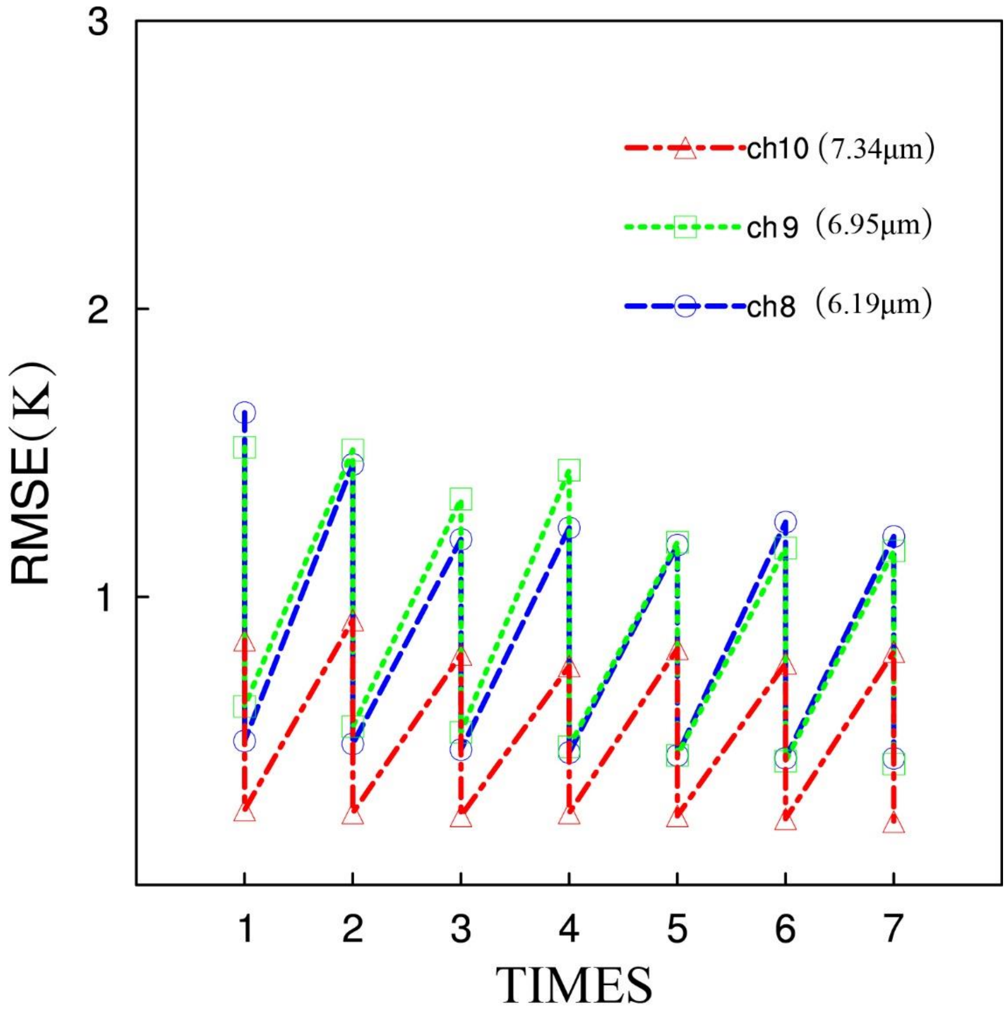


Fig. ~~9~~10 Time series of the RMSE for the brightness temperature (unit: K) with assimilation times before and after the data assimilation.

~~a)~~ ~~b)~~

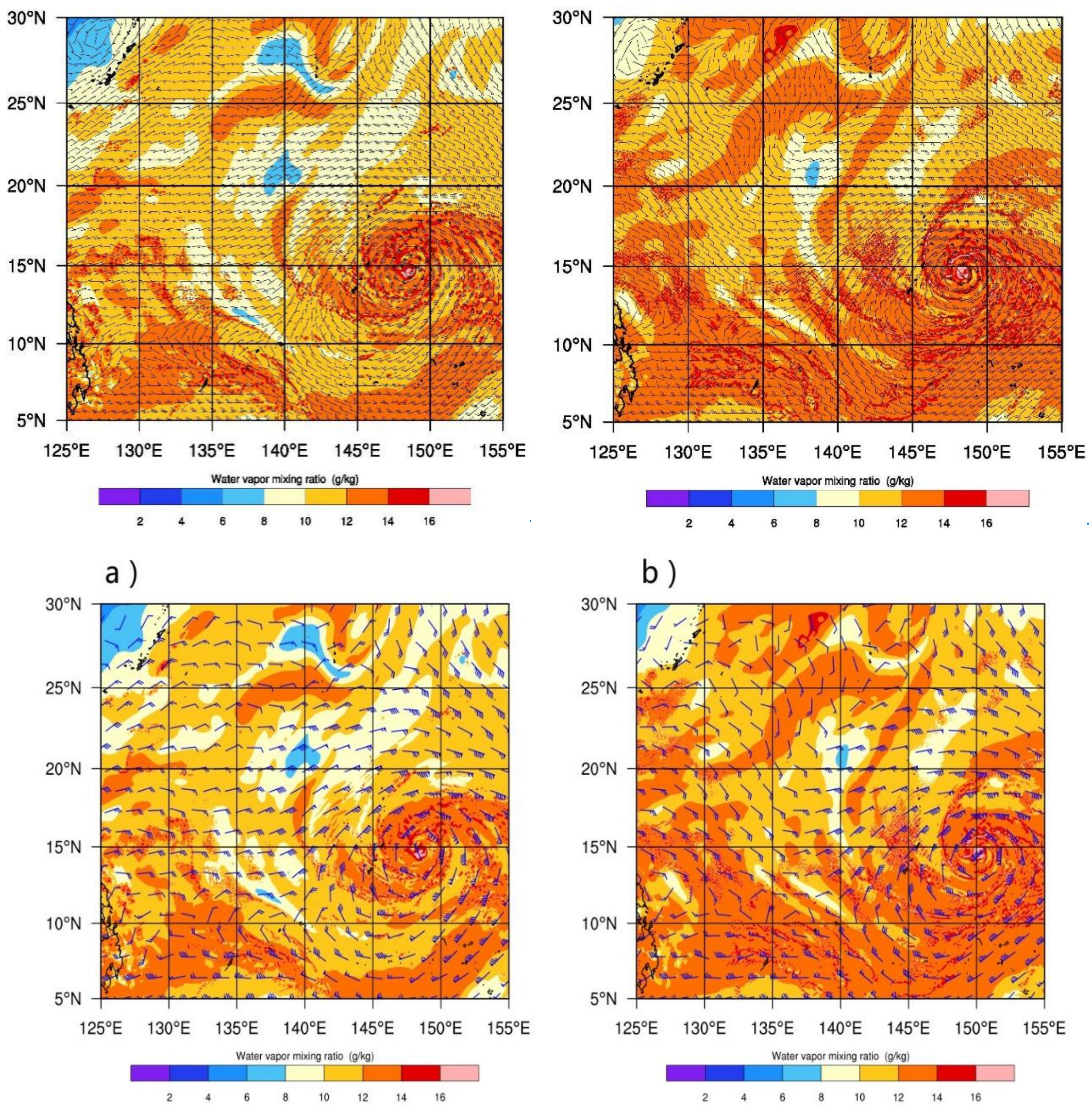
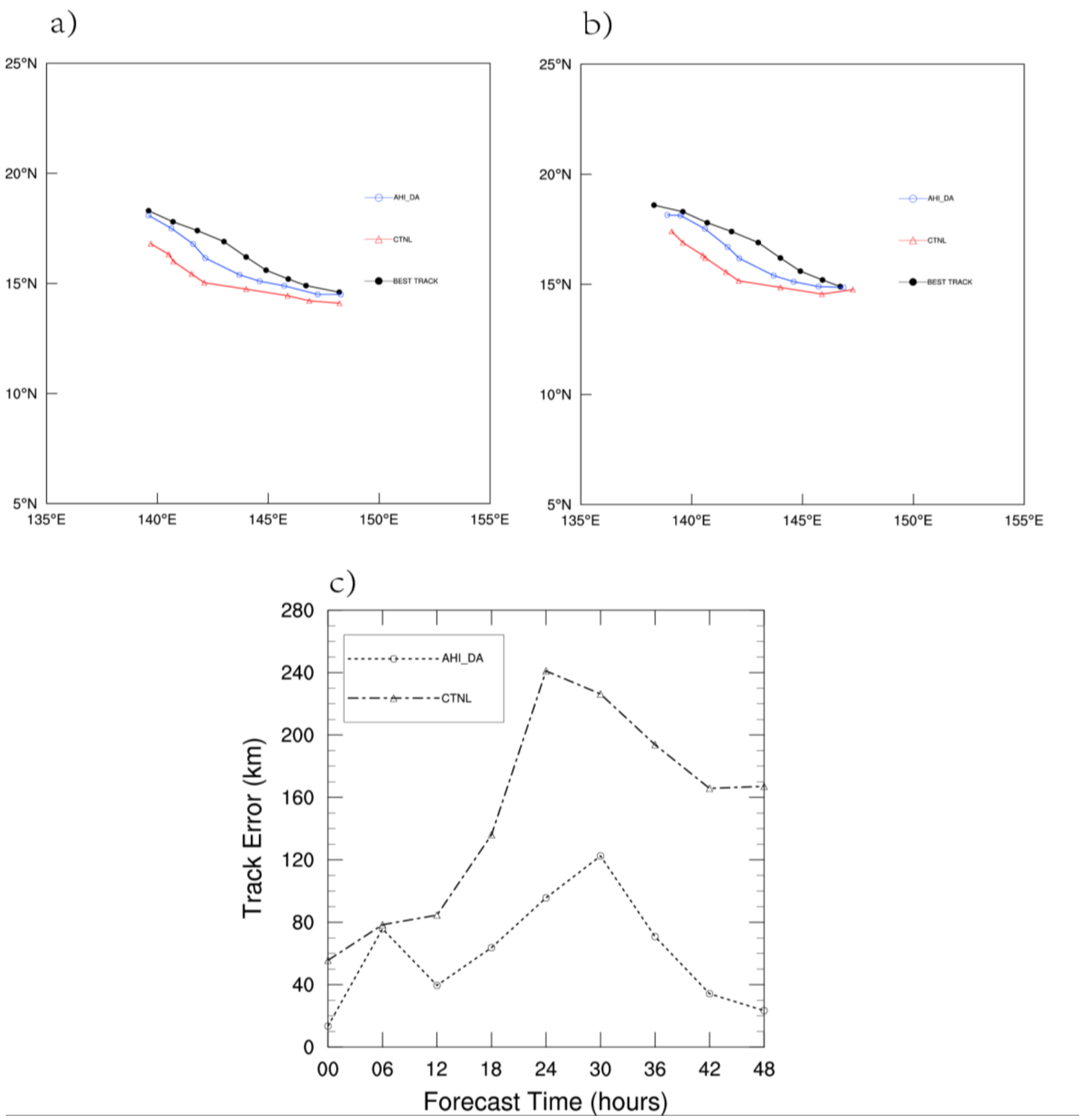


Fig. ~~10~~ 11 The surface wind speed (vectors, unit: m s^{-1}) and water vapor (colored, unit: g/kg) for (a) CTNL; (b) AHI_DA at 850 hPa at 0000 UTC 2 August 2015.


a)
b)
c)
AHI_DA
CTNL
BEST TRACK
25°N
20°N
15°N
10°N
5°N
135°E
140°E
145°E
150°E
155°E
Track Error (km)
Forecast Time (hours)
280
240
200
160
120
80
40
0
00
06
12
18
24
30
36
42
48

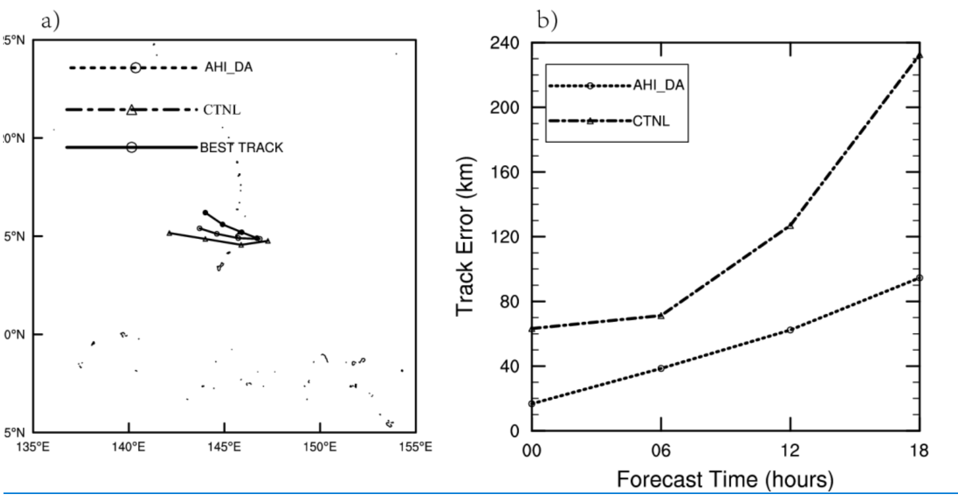
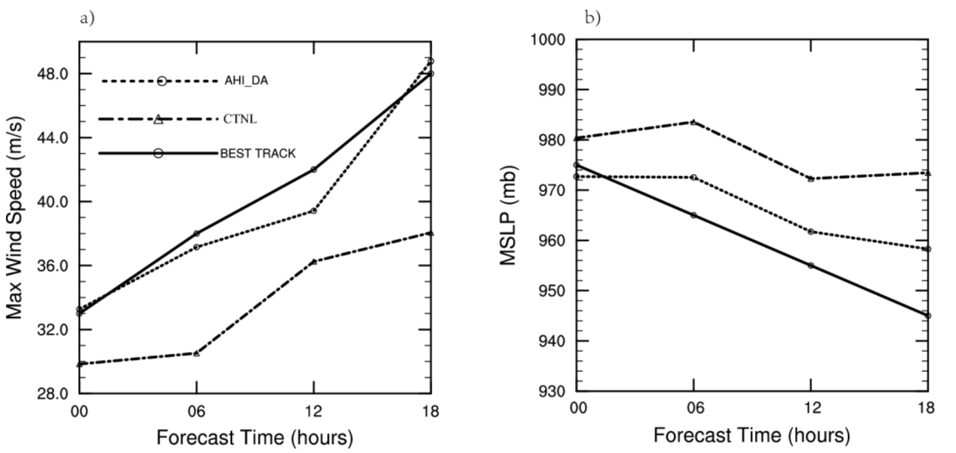

a)
b)
AHI_DA
CTNL
BEST TRACK
5°N
0°N
135°E
140°E
145°E
150°E
155°E
Track Error (km)
Forecast Time (hours)
240
200
160
120
80
40
0
00
06
12
18

Fig. ~~11~~ 12 The ~~18~~48-hour ~~(a)~~ predicted tracks (a), from 0000 UTC 2 August to 0000 UTC 4 August, (b) from 0600 UTC 2 August to 0600 UTC 4 August 2015, (c) averaged track errors (unit: m s^{-1}) for the two forecasts. ~~of Soulder from 0600 UTC 2 to 0000 UTC 3 August 2015.~~



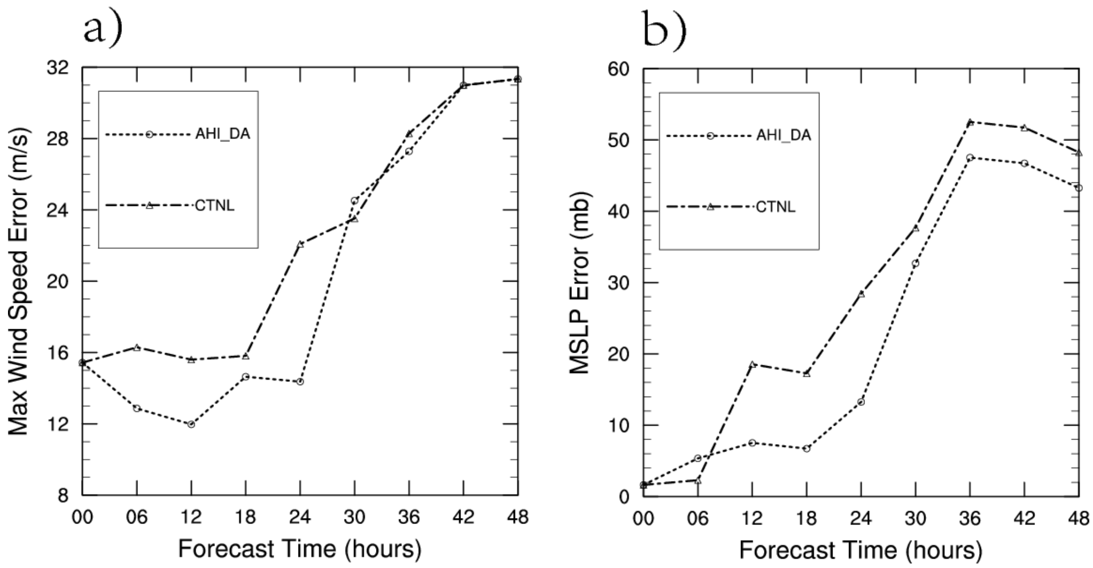


Fig. ~~12~~ 13 The ~~18~~48-hour ~~predicted~~ (a) maximum surface wind (unit: m s^{-1}), (b) minimum sea level pressure (unit: hPa) of Soulder averaged from ~~0600 UTC 2 to 0000 UTC 3 August 2015~~two forecasts.