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Key Points:

- Targeted observing was performed for Typhoon Maria (2018) using FY-4A Geostationary Interferometric Infrared Sounder (GIIRS) with a high-temporal-resolution of 15 min
- GIIRS assimilation with different temporal resolutions shows the added value of high-temporal hyperspectral radiances from a geostationary satellite
- High-temporal GIIRS assimilation captured more detailed atmospheric structures and stronger warm anomalies than the control experiment

Supporting Information:

Supporting Information may be found in the online version of this article.

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Impact of High Temporal Resolution FY-4A Geostationary Interferometric Infrared Sounder (GIIRS) Radiance Measurements on Typhoon Forecasts: Maria (2018) Case With GRAPES Global 4D-Var Assimilation System

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Abstract Targeted observations for Typhoon Maria (2018) using the Geostationary Interferometric Infrared Sounder (GIIRS) at a temporal resolution of 15 min provide unprecedented information for impact studies of high-temporal-resolution from geostationary hyperspectral IR sounders. This study investigates the impacts of different temporal resolutions for GIIRS assimilation on Maria analyses and forecasts. Results reveal that assimilating higher resolution data captures more detailed temporal and spatial structures and stronger warm anomalies. Additionally, the track forecast for Maria from assimilating higher temporal resolution GIIRS radiances is better than those from assimilating radiances with lower temporal resolution, and both are better than the control experiment. The accuracy of the different temporal resolutions GIIRS experiments (from 3 h to 15 min) is improved (from 18% to 43%), and the intensity forecast errors are also reduced (from 12% to 18%). Meanwhile, high-temporal GIIRS assimilation also improves the coastal precipitation forecasts during typhoon landfall.

Plain Language Summary Satellite observations are the most important data source for the atmospheric observing system. In particular, high-spectral-resolution infrared data is very important since it provides more accurate atmospheric profiles with high vertical resolution. However, most of the previous studies are based on high-spectral-resolution infrared sounders from low earth orbit satellites that cannot provide continuous monitoring of the atmospheric temperature and moisture profiles at small spatial scales, which appears especially important for high impact weather events, such as typhoons or hurricanes. The impacts of the Geostationary Interferometric Infrared Sounder at a temporal resolution of 15 min on Typhoon Maria forecasts, such as track forecasts and central sea level pressure predictions, were evaluated in this work. Assimilation experiments with different temporal resolutions for Geostationary Interferometric Infrared Sounder (GIIRS) clearly show higher temporal resolution GIIRS data provides better forecasts than lower resolution observations.

1. Introduction

Tropical cyclone (TC) forecasts depend highly on the accuracy of atmospheric temperature and humidity structures in the initial field of the model. Satellite sounder observations, such as microwave and infrared (IR) sounders, are the main source of temperature and water vapor information over the tropical ocean where there are relatively sparse conventional in situ observations (Li & Liu, 2009; Wang et al., 2014, 2017). Compared with IR imagers, hyperspectral IR sounders, such as the Infrared Atmospheric Sounder Interferometer (IASI), the Atmospheric Infrared Sounder (AIRS) and the Cross-track Infrared Sounder (CrIS) (Menzel et al., 2018), have thousands of channels that can provide accurate and detailed atmospheric temperature and humidity information with high vertical resolution (Wang et al., 2007).

The assimilation of hyperspectral IR sounder data has shown positive impacts on numerical weather prediction (NWP) (Le Marshall et al., 2006; A. Smith et al., 2015; W. L. Smith et al., 2020), especially for high impact weather forecasts, such as for tropical storms (Li & Liu, 2009). Reale et al. (2009) and Zheng et al. (2015) found the impact of AIRS assimilation on model forecasting system was positive and the track errors were smaller after AIRS assimilation. Wang et al. (2017) assimilated cloud-cleared CrIS radiances for two storm cases and the results showed that the hurricane track was further improved compared with assimilating CrIS original radiances. However, AIRS/IASI/CrIS observations used in previous studies are from low earth orbit (LEO) satellites, meaning its temporal resolution is limited in atmospheric stability monitoring applications (Smith et al., 2020). In contrast, geostationary (GEO) IR sounders can provide breakthrough measurements on the time evolution of atmospheric vertical structures (Li et al., 2011; Schmit et al., 2009). Li et al. (2018) also explained the importance of GEO hyperspectral IR sounders to nowcasting and NWP applications compared with existing LEO hyperspectral IR sounders. A GEO hyperspectral IR sounder can provide continuous observations for a particular region, which enables more sensitivity for monitoring atmospheric changes.

The Geostationary Interferometric Infrared Sounder (GIIRS) is the first hyperspectral IR sounder flying on a GEO weather satellite. Onboard the FY-4A satellite (Yang et al., 2017) launched on December 11, 2016, GIIRS provides unprecedented continuous temperature and humidity profile information with high-temporal and spatial vertical resolutions, which is required for monitoring, warning and forecasting high-impact weather events (Li et al., 2011; Schmit et al., 2009). GIIRS has 1,650 spectral channels, including 689 long-wave (LW) IR channels (700–1,130 cm^{-1}) and 961 middle-wave (MW) IR channels (1,650–2,250 cm^{-1}) (Yang et al., 2017). It can scan the atmosphere quickly (e.g., 15 min for 54 fields of regard for the Maria case in this study) at a spectral resolution of 0.625 cm^{-1} and a spatial horizontal resolution of about 16 km. Therefore, studying the impact on high-impact weather forecasts of a GEO hyperspectral IR sounder, with a focus on high temporal resolution using GIIRS observations, is an important research topic. For example, Li et al. (2018) demonstrated the added value from GEO hyperspectral IR sounder data for severe local storm forecasts in a regional Observing System Simulation Experiment (OSSE). Okamoto et al. (2020) also explained the advantages of GEO satellite hyperspectral IR data for both regional and global NWP models. Using a hybrid OSSE, Wang et al. (2021) demonstrated the improved local severe storm forecasts including atmospheric temperature, moisture, wind and precipitation forecasts when assimilating hyperspectral IR sounder data in a regional NWP. Wu et al. (2020) indicated that a high-temporal IR imager could improve rainstorm predictions. However, the impacts from different resolutions of hyperspectral IR sounder observations have not been studied systematically and discussed in previous studies. That aspect is highlighted in this study. To evaluate the impact of high-temporal hyperspectral IR sounder radiances on forecasting high-impact weather events, such as Typhoon Maria (2018), assimilation experiments with four different temporal resolutions (15 min, 30 min, 1 h, and 3 h for GIIRS radiance measurements) are carried out. The findings provide better understanding of the importance of high temporal GEO IR sounder observations for NWP applications, as well as the scientific implications with respect to the requirements for and planning of future GEO hyperspectral IR sounder systems.

2. Data and Methodologies

2.1. GIIRS Observations

Typhoon Maria (2018) was a destructive and powerful TC in the northwest Pacific Ocean that began July 4, 2018 and affected the Mariana Islands. After crossing the Yaeyama Islands and impacting Taiwan on July 10, Maria ultimately made landfall over Fujian, China early on July 11, before dissipating the next day. The typhoon caused 2 deaths and $ 628 million (USD) in damages (https://en.wanweibaike.com/wiki-Typhoon%20Maria%20(2018)). A 36 h targeted observing period was performed for Maria using FY-4A GIIRS starting at 0000 UTC on July 10, 2018. During this period, GIIRS observed a fixed area affected by Typhoon Maria (12°N ~ 36°N, 108°E ~ 138°E, as shown in Supporting Information [SI] Figure S1a) at a temporal resolution of 15 min, with continuous observations ending at 1200 UTC on July 11, 2018. The GIIRS data provided unprecedented information for an impact study of high-temporal-resolution hyperspectral IR radiances.

2.2. GRAPES Global 4D-Var Data Assimilation System

The Global/Regional Assimilation and PrEdiction System (GRAPES)—Global Forecast System (GFS) 4D-Var was used in this study (Shen et al., 2020). Its assimilation time window is 6-h, the horizontal resolution is 0.25 × 0.25°, and it has 62 vertical model levels. More details about GRAPES-GFS 4D-Var can be found in Zhang et al. (2019).

2.3. Experimental Design

To study the impact of high-temporal GIIRS observations on Typhoon Maria forecasts, five experiments were conducted, including a control experiment (CTRL for simplicity) and four GIIRS assimilation experiments (CTRL + GIIRS radiance) with different assimilation time slots for GIIRS (15 min, 30 min, 1 h, and 3 h, respectively) within the 6-h assimilation window. The observations assimilated in the CTRL experiment are shown in SI Table S1a; the CTRL is the operational configuration for our study in a research environment which is a frame designed for research to operation (R2O) at the China Meteorological Administration (CMA). The data used in the four GIIRS experiments include those used by the CTRL and GIIRS radiance measurements with different temporal resolutions. Assuming that the start time of an assimilation cycle is 0300 UTC, the CTRL and four GIIRS data assimilation experiments are shown in SI Table S1b.

In this study, because the start time of the GIIRS targeted observations is 0000 UTC July 10, 2018 and Maria dissipated the next day after landfall, the assimilation cycling runs every 6 h from 2100 UTC 9 July to 0300 UTC 10 July, followed by 36 h forecasts. The background field at the initial time is from the GRAPES operational system. The thinning mesh for GIIRS radiances is every 100 km. The channel selection is shown in SI Figure S1b and Table S2 (Yin et al., 2019), and it includes channels covering the upper, middle and lower troposphere. In addition, only the GIIRS LW channels are assimilated in this study. The bias correction (BC) for GIIRS is based on its detector dependent biases; more details about the GIIRS preprocessing (e.g., hamming apodization) and BC steps can be found in Yin et al. (2020). In addition, a background check based on the differences between observations and simulations ($|O\text{-}B| < 3K$) is used in the quality control (QC).

3. Impacts of GIIRS Temporal Resolution on Maria Analysis and Forecasts

3.1. Differences Between the Observations and Simulations

The initial fields of forecast (or background/first-guess fields), including the temperature, moisture, and other atmospheric information, can be adjusted by satellite observations through data assimilation. The differences between observations and simulations (O-B) from assimilation experiments are analyzed and discussed below for better understanding the data impacts from the different temporal resolutions of the GIIRS radiance measurements.

SI Table S3 shows the brightness temperature (BT) differences (BTDs) between the observations and simulations (from background) after BC of GIIRS channel 27 (716.250 cm^{-1}, with a weighting function or radiance sensitivity function peaking at around 500 hPa) and channel 87 (753.750 cm^{-1}, with a weighting function or radiance sensitivity function peaking at around 850 hPa) for the 15 min, 30 min, 1 h, and 3 h GIIRS experiments, respectively. As expected, the number of assimilated data varies greatly in the different experiments, increasing from around 200 (3 h) to above 2,000 (15 min). In addition, the biases of O-B are positive for channel 27 (∼500 hPa), and the biases are 1.08, 0.42, 0.28, and 0.19 K for the 3 h, 1 h, 30 min, and 15 min experiments, respectively. The bias decreases when the GIIRS temporal resolution is higher, while the standard deviation (STD) of observations minus background for this channel is around 0.9 K for all four experiments, making it relatively stable. As for channel 87, the biases are negative, around −0.3 K, while the standard deviation is slightly smaller when the GIIRS temporal resolution is higher (from 1.19 K [3 h] to 1.05 K [15 min]).

Figure 1 shows the temporal variations of observed BTs (color), the simulated BTs from the background field (black) of GIIRS channel 100 (761.875 cm^{-1}, with a weighting function or radiance sensitivity function peaking at around 1,000 hPa) averaged over the whole GIIRS observed region. Each point represents an average of 15 min. Figures 1a–1d represent 3 h, 1 h, 30 min, and 15 min GIIRS observations, respectively, while the background lines represent 15 min variation in Figures 1a–1d (some points in Figure 1 are empty due to the lack of observations). As seen in the image, the variation in the background field (black line) is high during the assimilation period. Therefore, the model needs sufficient detailed information about the variation in atmospheric structure in both time and space to adjust the initial field (Schmit et al., 2009). In

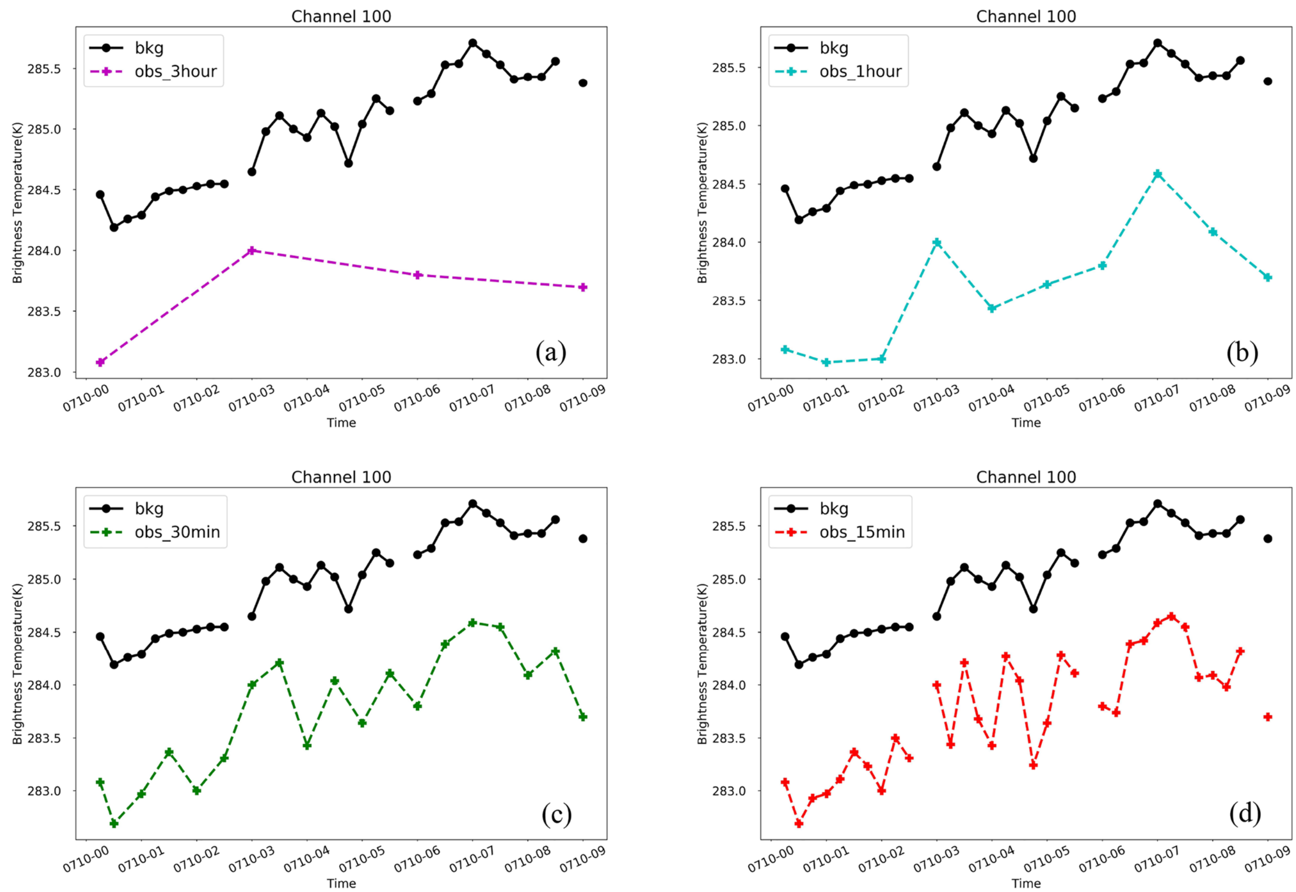

Figure 1. Temporal variations in the Geostationary Interferometric Infrared Sounder (GIIRS) observed BTs and the simulated BTs from background fields (black line) for channel 100 averaged over the whole GIIRS observed region. Four GIIRS experiments (3 h, 1 h, 30 min, and 15 min) are shown as (a), (b), (c) and (d), respectively.

addition, studies (Dunion et al., 2016; Tang & Zhang, 2016) showed that the TC diurnal variation may be related to typhoon structure and intensity change, which indicates that continuous atmospheric information is important for typhoon forecasts. However, for GIIRS assimilation with a lower temporal resolution (3 h experiment, see Figure 1a), the temporal change in GIIRS observations is significantly lower, which does not match the temporal variation requirements of the background field (black line). The temporal variations in observed BTs fluctuate significantly more with the increase in temporal resolution (as shown in Figures 1b–1d). With GIIRS observations every 15 min for the assimilation (Figure 1d), the GIIRS observed BTs vary with large fluctuations, which indicates that GIIRS does capture more detailed temporal and spatial temperature and humidity structure information. Therefore, it can meet the demand of the background field change, and thus improve the analysis field.

3.2. Contribution of Observations to Analysis

The model atmospheric fields at the analysis time can be affected directly by observations, so the influence of different temporal sets of GIIRS observations on the model analysis can be understood by evaluating the differences between the analyses fields of GIIRS and CTRL over time. Figure 2 represents the temperature field differences between GIIRS and CTRL (GIIRS 3 h, 1 h, 30 min, and 15 min, respectively, minus CTRL) at 0000 UTC on July 10, 2018. More observations are used in the assimilation system with higher temporal resolution (see SI Table S3), which brings more atmospheric information into the assimilation. The additional observations from higher temporal resolution could draw the analysis fields further closer to the observed values. Li et al. (2018) also suggested that GEO IR sounders with higher temporal resolution are important to NWP models due to more observations. Figure 2 displays the temperature field differences

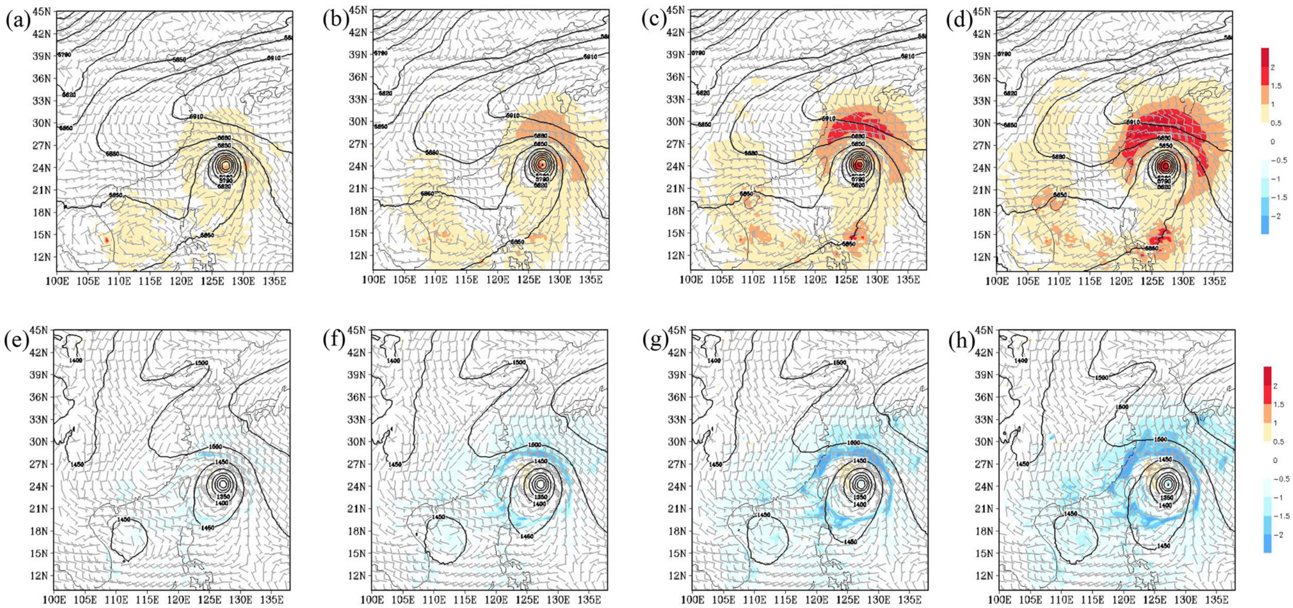

Figure 2. Temperature differences between Geostationary Interferometric Infrared Sounder (GIIRS) and control experiment (CTRL) (GIIRS 3 h, 1 h, 30 min, and 15 min minus CTRL) (shaded), geopotential heights of GIIRS (contour), and wind vectors of GIIRS at 500 hPa (top) and 850 hPa (bottom) at 0000 UTC on July 10, 2018. Four GIIRS experiments are shown (from left to right represent 3 h, 1 h, 30 min, and 15 min temporal resolutions, respectively).

between GIIRS and CTRL (shaded areas). The increments are located around the typhoon center and the edge of clouds, which are consistent with the observation range (SI Figure S1a). Generally, the temperature at 500 hPa increases while the temperature at 850 hPa decreases in this particular case due to GIIRS radiance assimilation. This result is also consistent with the bias of O-B (as shown in SI Table S3). Furthermore, with higher temporal resolution, the areas showing temperature differences are larger, and the values of the differences are also bigger. At 500 hPa, the maximum value of the temperature analysis differences for the 15 min temporal resolution is larger than 2 K (Figure 2d), which is around 0.5 K warmer than that of the 30 min temporal resolution (Figure 2c), 1 K warmer than that of the 1 h temporal resolution (Figure 2b), and 1.5 K warmer than that of the 3 h temporal resolution (Figure 2a). At 850 hPa, the temperature analysis differences have a similar magnitude however there is a drop in temperature. The lowest value of the temperature analysis differences is around 1.5 K colder from the 15 min temporal resolution (Figure 2h) when compared to that of the 3 h temporal resolution (Figure 2e). It can be seen that the higher temporal resolution of GIIRS is more capable of capturing the changes in atmospheric temperature and humidity information, and thus results in larger temperature increments.

3.3. Impacts on Warm Core

The warm core is an important feature of typhoons, and its vertical structure is closely related to the intensity, rapid intensification (RI), and development of typhoons (Emanuel, 1991; Wang et al., 2016). Typically the vertical structure of the warm core has the following features: the maximum temperature anomaly occurs in the upper troposphere of the typhoon center (about 200–400 hPa), and there is a large radial temperature gradient in the vertical zone outboard the center. The vertical structure changes with its intensity: the larger the area of the warm core, the greater the typhoon intensity. In principle, since GIIRS provides valuable information on vertically resolved temperature, such structures can be displayed effectively by assimilating hyperspectral GIIRS observations. Therefore, analyzing the typhoon warm core structure is helpful for understanding the influence of different model initial fields on typhoon evolution. Figure 3 shows the vertical cross sections of temperature (shaded contours) and meridional wind (gray contours) anomalies for the four GIIRS assimilation experiments and CTRL at 0000 UTC, July 10, 2018. The temperature anomaly is calculated according to the environment temperature, which is based on the typhoon center to calculate the average temperature within a longitude range of 15° for each layer in this study. The

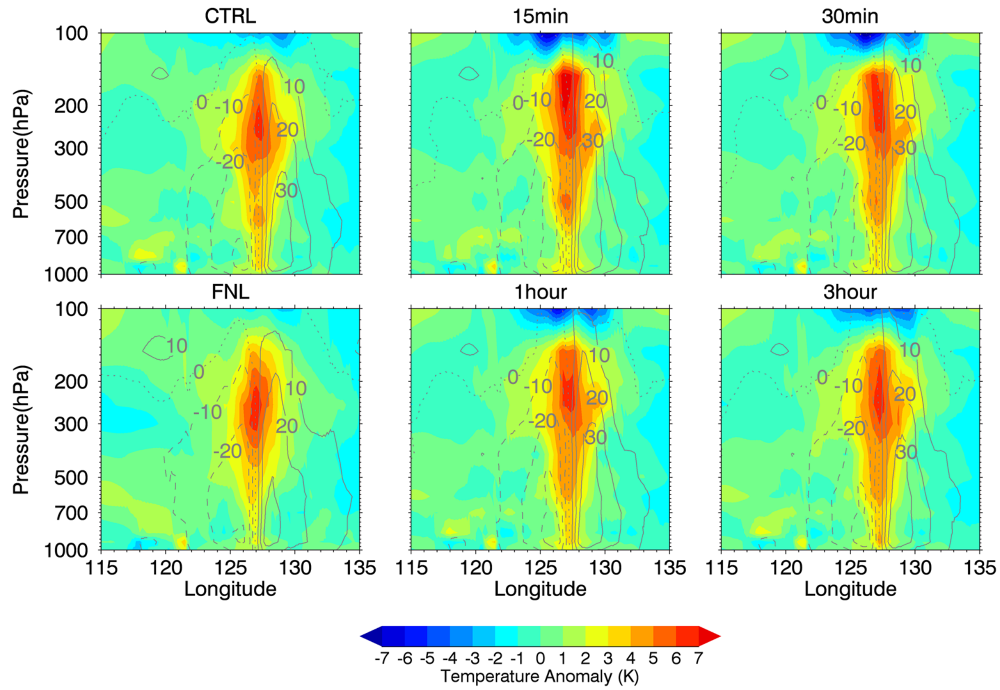

Figure 3. Vertical cross sections of temperature anomalies (shaded contours) calculated from various experiment sets for Typhoon Maria along 24.0°N latitude at 0000 UTC, July 10, 2018. Gray contours show the meridional wind anomaly in m s^{-1}. The anomaly is calculated based on the average value of the typhoon center within a longitude range of 15°.

temperature anomaly using FiNaL data (FNL) from NCEP at the same time is also given in Figure 3. More details on FNL can be found in National Centers for Environmental Prediction/National Weather Service/NOAA/U.S. Department of Commerce (2000).

The maximum temperature anomaly of the warm core (MWC) in each experiment is located at around 200 hPa, which is consistent with Wang et al. (2016). The MWC of the FNL temperature anomaly of 6.67 K is at 250 hPa. It is worth nothing that Gao et al. (2018) pointed out that FNL data generally underestimated Hurricane Edouard's (2014) warm core intensity, so Figure 3d is more for comparison rather than an accurate value. The MWC of CTRL is about 6.55 K, which is smaller than that of FNL, indicating that the strength of the typhoon is also underestimated by CTRL. After assimilating GIIRS, the MWC of the 3 h experiment increased to 6.68 K, which is larger than that of the CTRL, but still underestimated. The warm column area larger than 6 K in the GIIRS assimilation experiment grows with increasing GIIRS temporal resolution, with the MWC of the 15 min GIIRS experiment reaching 7.6 K. In addition, the peak MWC of the 15 min GIIRS experiment was found at 150 hPa (Figure 3a), which is higher than the 250 hPa of the CTRL and FNL. This result implies that the typhoon intensity prediction of the 15 min experiment could be more accurate. As revealed by Zhang and Chen (2012), the contribution of the upper-level warming core to the surface pressure change during Hurricane Wilma (2005) RI is twice as large as the contribution of lower-level warming, which indicates the importance of the upper warm core in RI. Furthermore, there is a clear cold temperature anomaly at 100 hPa for all four GIIRS assimilation experiments. The minimum cold anomaly of the 15 min GIIRS experiment is about −7.4 K, which is consistent with the results of Rivoire et al. (2016), indicating that the tropopause-level horizontal cooling magnitude of the TC is similar to that of the warm core, and may affect the strength of the TC. Larger meridional wind anomalies near the center of the typhoon can also be seen in the GIIRS assimilation experiment rather than CTRL, especially in the 15 min experiment (30 m s^{-1} contour in Figure 3).

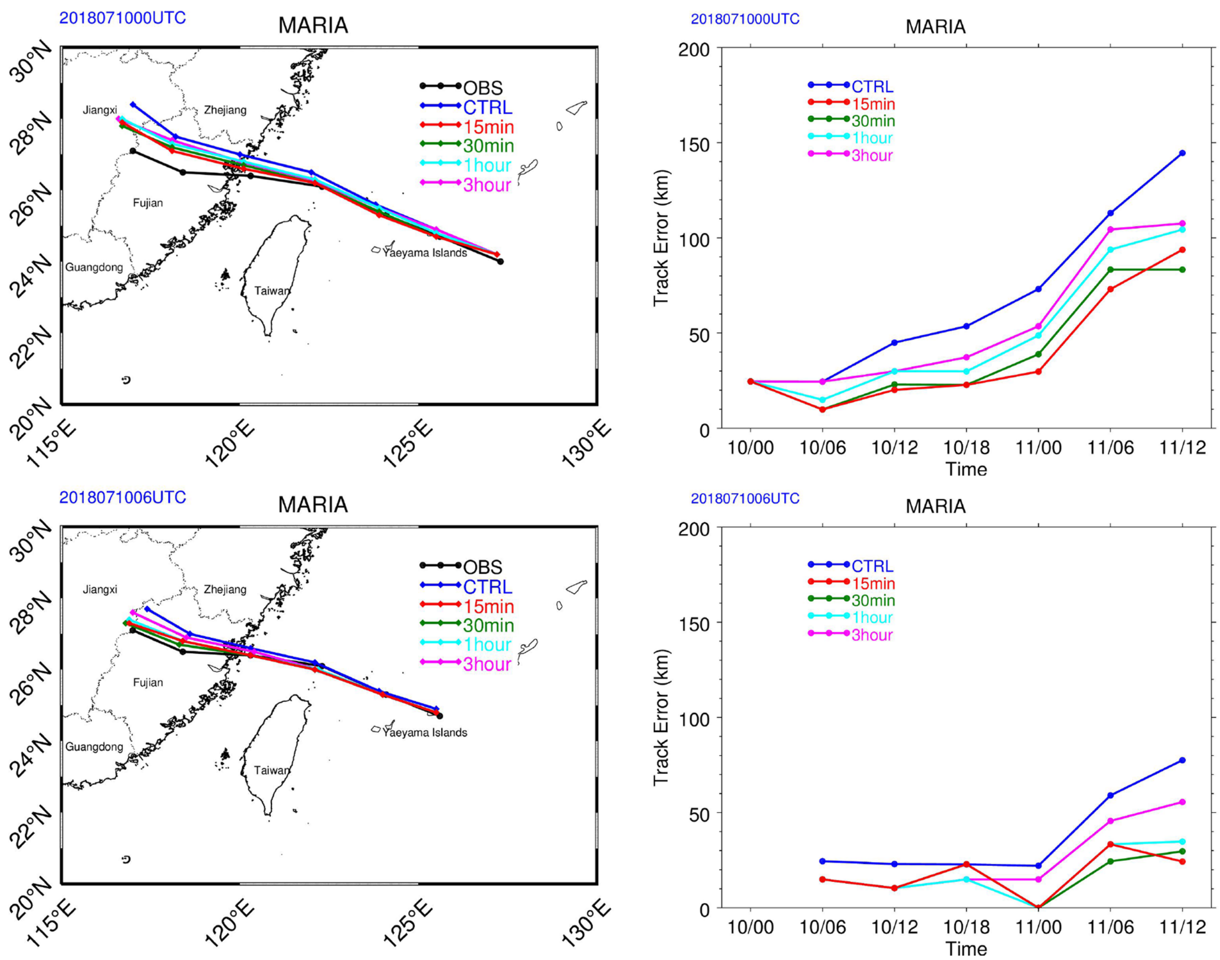

Figure 4. The 36 h/30 h track forecast for Typhoon Maria from 0000 UTC (top)/0600 UTC (bottom) on July 10, 2018. The black, blue, red, green, cyan, and magenta lines indicate the Best Track, control experiment, 15 min, 30 min, 1 and 3 h, respectively.

3.4. Impacts on Track and Rain Forecasts

Through the comparison of temperature increments and anomalies, we found that the assimilation of higher temporal resolution GIIRS radiances could bring more detailed temporal and spatial atmospheric structures into the model, which may improve track and pressure forecast accuracy of Maria to some degree. Figure 4 shows the track forecasts of Typhoon Maria from the CTRL (blue line), 15 min (red line), 30 min (green line), 1 h (cyan line), and 3 h (magenta line). The Observation Track (black line) is the best track from CMA. Because Maria dissipated after 1200 UTC on July 11, 2018, only 36 h/30 h predictions from 0000/0006 UTC on July 10, 2018 are displayed. In general, compared with the forecasts from the CTRL, the track forecasts after GIIRS assimilation are significantly closer to the Best Track. From 0000 UTC on 10 July, the 15 min (30 min/1 h/3 h) GIIRS assimilation experiment improves the track forecast, with the 36-h average track error being reduced by 43% (40%/28%/18%) when compared with the CTRL. The results indicate that the assimilation of GIIRS with a 4D-var system improves the track forecasts and that higher temporal resolution provides better forecasts. The central sea level pressure (SLP) prediction is also improved by about 18%, 16%, 14%, and 12% (24-h mean pressure error) for 15 min, 30 min, 1 h, and 3 h, respectively (not shown here). Also, there is substantial improvement in track forecast accuracy in GIIRS assimilation experiments from 0600 UTC on 10 July compared to the CTRL. The 30-h average track error of the 15 min GIIRS experiment is reduced by half to about 25 km, which is close to the GRAPES-GFS model spatial horizontal resolution. In addition, the track error of the CTRL is around 25 km (close to GRAPES-GFS resolution) from 1200 UTC on 10 July (not shown here), so it is hard to further improve the prediction from that time forward. Overall, assimilation of higher temporal resolution GIIRS data can adjust the model atmospheric fields better due to the availability of more detailed atmospheric information, which improves the track and pressure forecasts more compared to the lower temporal resolution experiments. In other words, the order of the forecast impact from GIIRS assimilation on Typhoon Maria from greatest impact to least is 15 min > 30 min > 1 h > 3 h > CTRL.

Every 6-h cumulative precipitation forecast after Maria landing in the Fujian province is shown in SI Figure S2. For brevity, only the CTRL and 15 min GIIRS experiments and station observations at 0600 UTC and 1200 UTC on July 11, 2018 are displayed. The assimilation of GIIRS data clearly improves the coastal precipitation forecasts during Maria's landfall period. At 0600 UTC, there are two precipitation centers larger than 60 mm/6 h, which are in the Fujian Province and Zhejiang Province, respectively. One of the heavy precipitation centers is predicted by the CTRL experiment, though the center position deviates from the observations. While the forecast of the 15 min GIIRS experiment not only predicted the two precipitation centers, it also shows center locations closer to those of the observations. Similarly, at 1200 UTC, the precipitation in the Fujian Province is more than 13 mm/6 h, most of which is between 25 and 60 mm/6 h. Compared with the CTRL, the 25–60 mm/6 h precipitation center of the 15 min GIIRS experiment is located in Fujian, and its precipitation area is larger, which is closer to the actual precipitation from station observations. Therefore, the 15 min GIIRS assimilation has a very positive impact on the precipitation forecast.

4. Summary and Future Perspective

On July 10, 2018, targeted observations over a period of 36 h were made for Typhoon Maria (2018) using FY-4A GIIRS with a high-temporal-resolution of 15 min. Based on these data, this study focuses on the added value of high-temporal-resolution GEO hyperspectral IR sounder data and compares the impact of different observation frequencies on Typhoon Maria, which has not been investigated in previous studies. Four different temporal resolutions are used in the assimilation (15 min, 30 min, 1 h, and 3 h); a control experiment is carried out for comparison and assessing the impacts of different temporal resolutions. It is shown that the analyses and forecasts are significantly different. GIIRS does provide more details of the vertical atmospheric temperature and moisture structure both temporally and spatially and improves upon the known positive effects of LEO hyperspectral IR sounders in the assimilation system (Li et al., 2018). The 15 min GIIRS experiment shows a continuous yet fluctuating tendency in observations which is not captured with lower assimilation frequency. It brings larger temperature increments to the model and has stronger warm anomalies. As a standard figure of merit we assess track forecasts with GIIRS assimilation compared to the CTRL run; clearly the GIIRS assimilation draws the forecasts closer to the Best Track. The track forecasts are improved quite significantly as track errors are reduced by 43% (15 min), 40% (30 min), 28% (1 h), and 18% (3 h) from 0000 UTC on July 10, 2018, respectively. Finally, the track forecast error is decreased to approximately 25 km (15 min GIIRS experiment from 0600 UTC on July 10, 2018), which is the size of the GRAPES-GFS model horizontal resolution. In conclusion, assimilating higher temporal resolution GIIRS data improves the track and SLP forecast errors more significantly compared to the lower time resolution experiments due to great detail about the atmospheric structure, resulting in better initial fields for the model forecast.

This work demonstrates the impact of GIIRS assimilation with different temporal frequencies on model prediction. The study is a first of its kind and realizes one of the promises expected from hyperspectral sounding in geostationary orbit. As such it confirms the expected value of geostationary hyperspectral sounding as spelled out by the WMO (World Meteorological Organization, 2019). The full benefit will emerge once there is a constellation of hyperspectral sounders covering the the lower and mid-latitudes of the Earth. While a European hyperspectral sounder on the Meteosat Third Generation (MTG) (Holmlund et al., 2021) is close to launch, no firm plans exist yet to cover other areas, with a notable gap over the United States. Further studies are needed to confirm the quantitative improvements using GIIRS in NWP. Such studies also serve as pathfinders for the applications of future hyperspectral sounders in geostationary orbit. In addition, this work supports the OSSE studies of Li et al. (2018), Okamoto et al. (2020), and Wang et al. (2021) to some extent using real measurements. They assessed the potential impacts of GEO hyperspectral IR sounders on NWP using an OSSE. In a future study, we will use a regional NWP model and data assimilation system with higher spatial resolution where the spatial scales of the model and observations are more compatible. The study also confirms a general request for more targeted observations with GIIRS at a temporal resolution of

15 min which necessitates breaks in the routine observation cycles with GIIRS in CMA operations. Another important future task is to assimilate GIIRS observations of humidity with the MW channels and to evaluate their potential for improved forecasts.

Data Availability Statement

The GIIRS targeted observations data targeted observations for Typhoon Maria used for Typhoon Maria in the study are available for free at Zenodo via http://doi.org/10.5281/zenodo.4656877 (Han & Yin, 2021a, 2021b). The simulation track data are available at http://doi.org/10.5281/zenodo.5055731 (Han & Yin, 2021a, 2021b).

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