# Improving Harvey Forecasts with Next-Generation Weather Satellites

## Advanced Hurricane Analysis and Prediction with Assimilation of *GOES-R* All-Sky Radiances

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**BACKGROUND.** Hurricane Harvey originated from an easterly wave in the tropical Atlantic Ocean but reemerged in the Gulf of Mexico as a tropical depression at 0000 UTC 23 August 2017 from the remnant of the original tropical cyclone. By 0600 UTC 24 August, Harvey had once again strengthened to a tropical storm. Over the course of the next few days, Harvey preceded to rapidly intensify into a major hurricane as it tracked to the northwest toward the Texas coast. The storm reached its peak intensity as a category 4 hurricane right before landfall in South Texas at 0400 UTC 26 August 2017. After landfall, Harvey slowly tracked inland before stalling, weakening to a tropical storm, and eventually tracking back toward and into the Gulf of Mexico before making another landfall in western Louisiana as a tropical storm. During this period after landfall in South Texas and prior to landfall in Louisiana, record rainfall occurred in the greater Houston region and throughout southeast Texas.

While Harvey brought catastrophic destruction from damaging winds and record-breaking rainfall to the Gulf Coast region, forecasters at NOAA were still able to provide valuable predictions of the storm's track and flooding potential days in advance, thanks in large part to the useful real-time guidance from operational numerical weather predication (NWP) models. However, all operational models failed to predict the rapid intensification (RI) of Harvey into a major storm, even for the forecasts initialized after the time RI had already begun; these operational systems include NOAA's regional-scale Hurricane Weather Research and Forecasting Model (HWRF), NOAA's Global Forecast System (GFS), and the integrated forecast system by the European Center for Medium-Range Weather Forecasts (ECMWF). Recent studies have shown that dominant sources of uncertainty in hurricane intensity and structure prediction for lead times of 3–5 days primarily come from poor initialization of the hurricane vortex which could be alleviated via high-resolution inner-core observations and/or efficient data assimilation methodologies, and from global models which could be due to the lack of a fine-resolution grid mesh that can resolve the eyewall and secondary circulations.

The current study seeks to examine the potential for improving Harvey's analysis and prediction through advanced ensemble-based assimilation of high-spatiotemporal all-sky infrared radiances from the next-generation geostationary weather satellite, *GOES-16*. *GOES-16* was launched in November 2016 and contains 6 visible and 10 infrared channels of all-sky brightness temperatures (BTs) with 1–2 km horizontal resolution available every 15 min under the routine surveillance mode and as frequent as every minute for a selected target subregion. Compared to its

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predecessor *GOES-13, GOES-16*—also widely known as *GOES-R* since it is the first in the "R" series of the U.S. geostationary infrared satellites—has about 3 times more channels, 4 times better resolution, and 5 times faster scans. Similar geostationary satellites such as the Japanese *Himawari-8/-9* are now also in orbit, and *GOES-S,* with identical capabilities to *GOES-16,* was launched on 1 March 2018 (now renamed as *GOES-17*). Recent studies have shown potential for assimilating high-resolution all-sky radiances from these next-generation geostationary satellites for tropical cyclone predictions. The uniqueness of the current study is that Harvey is the first major hurricane that was captured by *GOES-16* whose intensity prediction is shown to benefit greatly from assimilation of *GOES-16* radiance; Harvey's intensity was poorly forecasted by operational NWP models.

**METHODOLOGY AND EXPERIMENTAL DESIGN.** Satellite observations of particular interest for this study are the BTs (also referred to as radiances) from *GOES-16.* In this proof-of-concept study on its potential significance for hurricane analysis and prediction, real-data BTs from only one of *GOES-16's* water vapor channels (channel 8, wavelength is 6.19 $\mu$m) are assimilated every hour over a 24-h period. This is one of three water vapor channels that are responsive to tropospheric temperature and moisture profiles; these three channels are highly correlated in the inner-core regions so only one channel is assimilated for this pilot study.

The advanced data assimilation system used for assimilating the *GOES-16* all-sky radiance is the ensemble Kalman filter (EnKF) hurricane analysis and forecast system, developed at the Pennsylvania State University (PSU), which is built around the Advanced Weather Research and Forecasting Model (WRF-ARW) and the Community Radiative Transfer Model (CRTM). To assimilate all-sky BTs, including cloud-affected BTs with large representative errors, we employ adaptive observation error inflation (AOEI). The successive covariance localization method (SCL), which is designed to capture various scales, is also applied with a 30-km radius of influence for BT observations thinned every 12 km and with a 200-km radius of influence for BT observations thinned every 18 km. The covariance relaxation method with coefficient of 0.75, together with an adaptively estimated spatially homogeneous multiplicative inflation factor, is used to maintain a sufficient ensemble spread and to avoid filter divergence. The WRF-EnKF has 60 ensemble members with 3-km horizontal grid spacing.

Two WRF-EnKF experiments are conducted: one assimilating all conventional in situ and remotely sensed data for the operational GFS analysis [WRF(conv)], except for clear-sky satellite radiances but including atmospheric motion vectors; the other the same as WRF(conv) but also assimilating *GOES-16* all-sky satellite radiances [WRF(GOES16+conv)]. The current study focuses on the impacts of all-sky radiances in the hurricane inner-core region. The WRF-EnKF analysis is linearly relaxed every 6 h to the operational GFS analysis from the 300- to 600-km radius; within 300 km the analysis is completely from WRF-EnKF and outside 600 km completely from the operational GFS analysis, which benefited greatly from assimilation of clear-sky radiances.

**RESULTS FROM ASSIMILATION OF ALL-SKY *GOES-16* RADIANCE FOR INNER-CORE INITIALIZATION.** Figure 1 shows a comparison of BTs simulated by the PSU WRF-EnKF analyses WRF(GOES16+conv) versus WRF(conv) and the corresponding *GOES-16* 7.35-$\mu$m channel-10 observations (hereafter referred to loosely as "independent" since only channel-8 data were assimilated) of Hurricane Harvey at selected times prior to its intensification into a major hurricane. The additional assimilation of *GOES-16* all-sky radiances, beyond conventional observations alone, results in WRF-CRTM simulated radiances that progressively better match the independent *GOES-16* observations with regards to both cloud intensity and patterns. In particular, the EnKF-analyzed radiance in WRF(GOES16+conv) displays strong agreement with independent brightness temperature observations in regions of strong inner-core convection near the center of the domain, as well as the peripheral rainbands evolving in different sectors of the outer region. Furthermore, even the clear-sky regions demonstrate good agreement with independent observations, including the correct depiction of similar gradients in atmospheric water vapor. In contrast, the WRF analysis without the *GOES-16* radiance data assimilation not only underestimates the intensity of cold cloud tops, but also poorly captures the structure of the incipient inner-core and outer rainbands (Fig. 1).

Moreover, Fig. 2 shows improved predictions of Harvey's intensity by the WRF Model initialized with the PSU WRF-EnKF assimilation of the *GOES-16* all-sky radiance while the track forecasts were both accurate up to landfall. Harvey's rapid

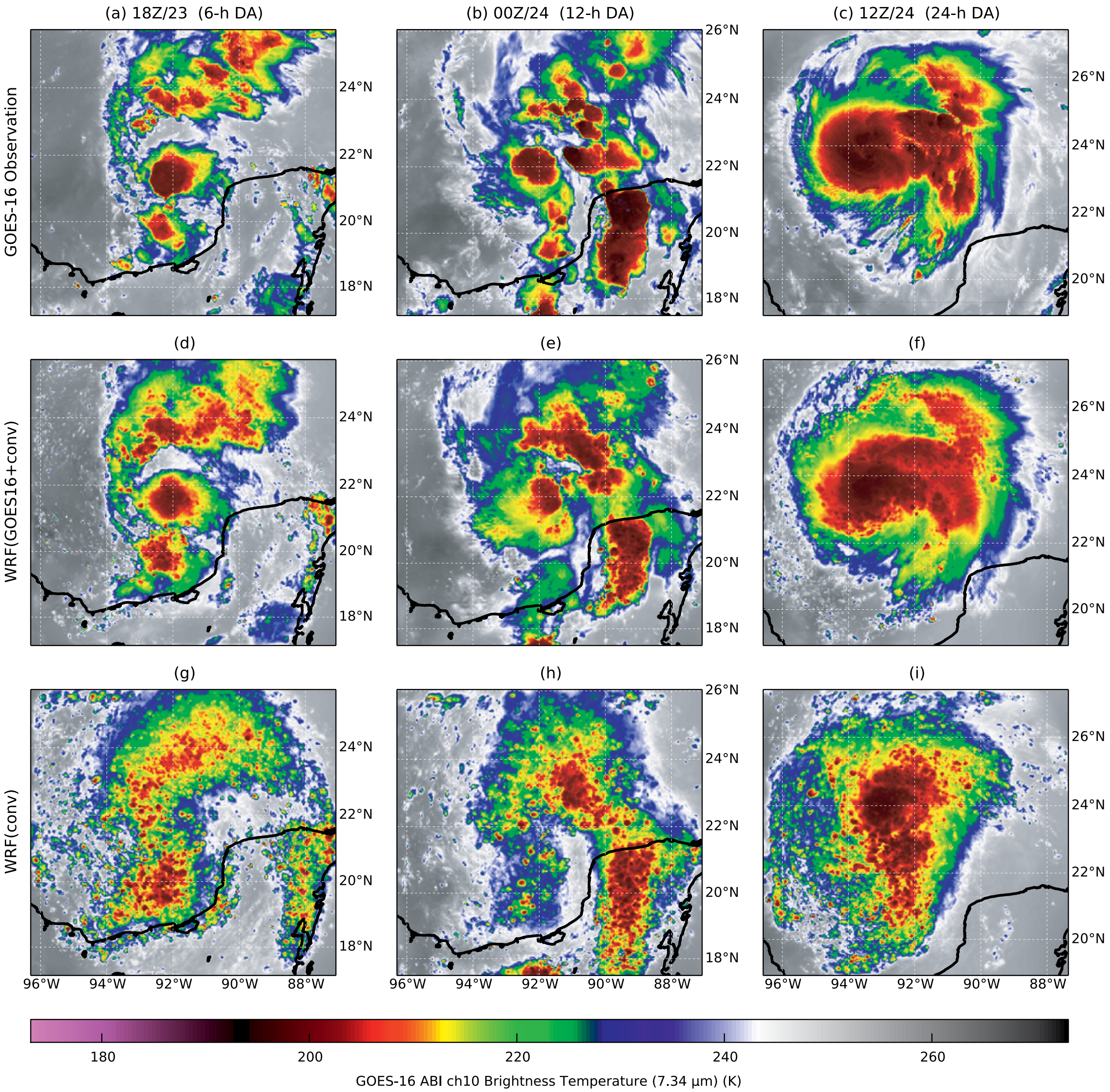

**Fig. 1. Impact of GOES-R on the Harvey analysis: (top) *GOES-16* observations vs the WRF-EnKF analysis (middle) with and (bottom) without *GOES-16* all-sky radiance assimilation valid at (left) 1800 UTC 23 Aug, (center) 0000 UTC 24 Aug, and (right) 1200 UTC 24 Aug 2017.**

intensification, timing, and peak intensity are captured by WRF(GOES16+conv). In contrast, the corresponding WRF forecasts without *GOES-16* all-sky radiance assimilation [WRF(conv)] barely develop Harvey into a category 1 hurricane and do not contain rapid intensification. The only difference between the two WRF forecasts is whether the *GOES-16* all-sky radiances (channel 8) are assimilated. More specifically, the WRF(conv) forecast initialized at 0000 UTC 24 August underpredicts Harvey's intensity but overpredicts the intensity when initialized at 1200 UTC 24 August. As a reference, the regional-scale forecast by NOAA's operational model HWRF initialized at the same time as the WRF(GOES16+conv) experiment was able to develop Harvey into a category 2 hurricane; however, it underestimated the peak intensity and timing. The operational HWRF forecast assimilated many more remote sensing and in situ observations but not the *GOES-16* all-sky radiance (nor did any other operational model, including GFS).

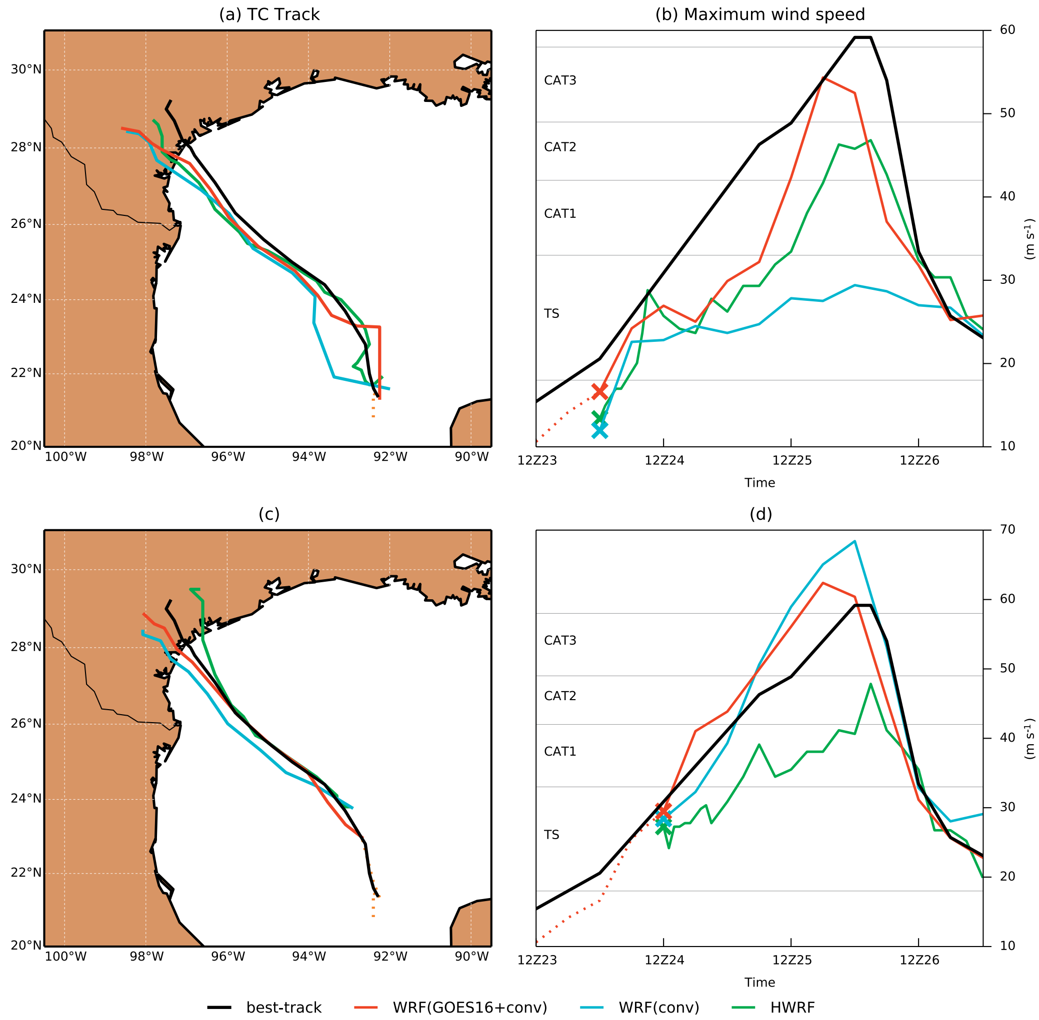

**FIG. 2. Comparison of Harvey's position and intensity forecasts by regional models: Harvey's (a),(c) track and (b),(d) maximum 10-m surface wind speed predicted by the WRF Model forecasts initialized with and without *GOES-16* all-sky radiance assimilation, but always including conventional observations, at 0000 and 1200 UTC 24 Aug 2017, respectively. The operational HWRF forecast and the NHC best-track estimates are also shown.**

## CONCLUDING REMARKS.

In summary, although more systematic investigations through large numbers of events and realizations will be necessary in the future before operational implementation, the current study highlights the potential for improving hurricane forecasts through the effective use of high spatiotemporal resolution all-sky radiance observations from the next-generation satellites (e.g., *GOES-16*). To the best of our knowledge, no cloudy radiance observations, either from geostationary or polar-orbiting satellites, are effectively assimilated into current-generation U.S. operational NWP models, which is at least partially responsible for the inferior performance of the U.S. operational model (GFS) to the counterpart operational model at the ECMWF, which has demonstrated significant forecast skill improvements resulting from cloudy-radiance assimilation. Other recent studies have shown also the promise of assimilating high-resolution all-sky radiances from the next-generation geostationary satellites for tropical cyclone predictions.

Note that, although the current study uses the same model configurations, model analysis, and observations as if they were operated in real time, it is also crucial to have high-performance computing facilities that can perform advanced hurricane analysis and forecasting with advanced NWP models and data assimilation algorithms in a timely manner. Moreover, given inherent uncertainties in hurricane prediction, we will also need to develop probabilistic forecasting strategies including—but not limited to—the use of sufficient ensemble size and sufficient model resolution for ensemble prediction systems initialized with flow-dependent initial condition uncertainties that are also generated from the advanced ensemble data assimilation techniques, such as the EnKF used in this study. Accurate probabilistic and ensemble forecasting will complement accurate deterministic forecasts empowered by next-generation satellite observations and next-generation numerical weather prediction models. These tools will be crucial for emergency managers and the general public to make informed decisions when facing hurricanes and other severe weather hazards.

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