The Impact of Dropwindsonde Data from the THORPEX Pacific Area Regional Campaign and the NOAA Hurricane Field Program on Tropical Cyclone Forecasts in the Global Forecast System

SIM D. ABERSON
NOAA/AOML/Hurricane Research Division, Miami, Florida

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ABSTRACT

Four aircraft released dropwindsondes in and around tropical cyclones in the west Pacific during The Observing System Research and Predictability Experiment (THORPEX) Pacific Area Regional Campaign (T-PARC) in 2008 and the Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region (DOTSTAR); multiple aircraft concurrently participated in similar missions in the Atlantic. Previous studies have treated each region separately and have focused on the tropical cyclones whose environments were sampled. The large number of missions and tropical cyclones in both regions, and additional tropical cyclones in the east Pacific and Indian Oceans, allows for the global impact of these observations on tropical cyclone track forecasts to be studied.

The study shows that there are unintended global consequences to local changes in initial conditions, in this case due to the assimilation of dropwindsonde data in tropical cyclone environments. These global impacts are mainly due to the spectral nature of the model system. These differences should be small and slightly positive, since improved local initial conditions should lead to small global forecast improvements. However, the impacts on tropical cyclones far removed from the data are shown to be as large and positive as those on the tropical cyclones specifically targeted for improved track forecasts. Causes of this unexpected result are hypothesized, potentially providing operational forecasters tools to identify when large remote impacts from surveillance missions might occur.

1. Introduction

The need for data acquisition over data-sparse tropical oceans to improve tropical cyclone analysis and forecasting has long been known (e.g., Riehl et al. 1956). The National Oceanic and Atmospheric Administration (NOAA) Hurricane Research Division (HRD) significantly improved numerical track forecasts using data from 20 “synoptic flow” experiments between 1982 and 1996 to gather observations in the tropical cyclone core and environment using NOAA WP-3D (P-3) research aircraft (Burpee et al. 1996). NOAA procured a Gulfstream IV-SP jet aircraft (G-IV) in 1996 and put it to use in operational “synoptic surveillance” missions in the environments of tropical cyclones that threaten the contiguous United States, U.S. Caribbean territories, and Hawaii. The missions led to 10%–15% reductions in GFS track forecast error during the critical watch and warning period before possible landfall (within the first 60 h), and small impacts in Geophysical Fluid Dynamics Laboratory (GFDL) track and intensity forecasts initialized at mission times (Aberson 2010). A similar program, Dropwindsonde Observations for Typhoon Surveillance near the Taiwan Region (DOTSTAR), has conducted missions around tropical cyclones in the west Pacific since 2003 (Wu et al. 2005, 2007). Wu et al. (2007) showed that the mean track error reductions in the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS), the Fleet Numerical Meteorology and Oceanography Center (FNMOC) Navy Operational Global Atmospheric Prediction System (NOGAPS), and the Japanese Meteorological Agency (JMA) Global Spectral Model (GSM), are 14%, 14%, and 19%, respectively.

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System Research and Predictability Experiment (THORPEX) Pacific Area Regional Campaign (T-PARC), the Tropical Cyclone Structure-08 (TCS08) experiment, and DOTSTAR, and multiple aircraft also participated in missions in the Atlantic in 2008. The mission timeline during the active aircraft sampling period in both the Atlantic and west Pacific (between 27 August and 2 October) is shown in Fig. 1. Previous studies have focused on those tropical cyclones whose environments were sampled, but since the global model in the study is spectral, local changes will have global impacts. The large number of missions and tropical cyclones in the Atlantic and west Pacific, and additional (unsampled) tropical cyclones in the east Pacific and Indian Oceans, allows for the global impact of the observations on tropical cyclone track forecasts to be examined. The expectation was that differences to forecast tracks from remote data (either in time or space) would be small, and somewhat positive, since improved local initial conditions should lead to small global forecast improvements. Other impacts due to the spectral nature of the model system would likely be random.1 Some cases do not follow this expected result, and hypotheses as to the causes are presented. Because the spectral nature of the forecasts cannot be removed from the forecasts, these hypotheses can be presented but not proved. The ultimate goal is to provide operational forecasters with tools to anticipate similar cases of large remote differences in the future so as to improve their forecasts.

Section 2 provides a brief review of the observing system experiment techniques used in the study. Section 3 examines the dropwindsonde data impact on track forecasts globally and by region. Section 4 delves into individual tropical cyclones and forecasts and the reasons for the impacts. Section 5 details the study’s conclusions.

2. Overview and procedures

A total of 18 tropical cyclones (6 in the Atlantic, 3 in the east Pacific, 8 in the west Pacific, and 1 in the Indian Ocean) occurred between 27 August and 2 October 2008, according to reports from the National Hurricane Center (NHC) and the Joint Typhoon Warning Center (JTWC). The environments of three tropical cyclones in the Atlantic and four in the west Pacific were sampled with aircraft2 (Fig. 1). NHC and JTWC best tracks are used for forecast verification.

The GFS version operational during September 2008 was used to assess the dropwindsonde data impact on forecasts. The system consisted of a quality control algorithm, a tropical cyclone vortex initialization procedure, a data assimilation step, and the Global Spectral Model. The quality control involved optimal interpolation and hierarchical decision making to evaluate the observations before they are assimilated (Woollen 1991). A vortex re-location procedure (Liu et al. 2000) places tropical cyclones in the first-guess field at their reported position, as in Kurihara et al. (1995). The analysis scheme was the grid-point statistical interpolation (Kleist et al. 2009) in which the background field (the previous 6-h forecast) was combined with observations with a three-dimensional variational multivariate formalism. The model resolution was T382L64. Two sets of model runs were completed: one with all dropwindsonde observations assimilated (hereafter “operational”), the other with them all excluded (hereafter “parallel”). The two are identical except for

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1 A local change will have a global impact on the spectral coefficients, but these changes will not be systematic.

2 In addition, numerous flights into the core and near environment of multiple storms were conducted during the period. For Hurricane Kyle, the core and near environment were sampled, but no synoptic, environmental sampling was conducted.
the assimilation of dropwindsonde data and the computer on which the two cycles were run. The model runs for the study were continuous cycles that began 6 h before the first flight and ended 12 h after the last mission (0000 UTC 27 August–1200 UTC 2 October).

3. Results by basin

The assimilation of dropwindsonde data improved average track forecasts globally by up to 13%, and these error reductions are statistically significant at the 90% level with serial correlation removed (Aberson and DeMaria 1994) through 84 h (Fig. 2). Average track forecast reductions in the west Pacific range from 4% to 23%, and those in the Atlantic from −3% to 12%. Average impacts are large but mixed in the other basins due to small sample sizes. The impacts in the Atlantic decrease with forecast time, becoming negligible by 84 h (Aberson 2002, 2010) but remain about constant in the west Pacific through 120 h. Pike and Neumann (1987) found that track forecasts were more difficult in the Atlantic than in the west Pacific, and Climatology and Persistence (CLIPER) errors (Aberson 1998; Aberson and Sampson 2003) confirm this for this sample (Fig. 3). Forecast improvement potential may be larger in the west Pacific than in the Atlantic since the forecast errors in the former are comparable to or larger than those in the latter.

4. Individual tropical cyclone results

Figure 4 shows average track forecast impacts from the assimilation of dropwindsonde data for the 8 tropical cyclones in the sample with more than 18 cases verifying at each forecast time; tropical cyclones with fewer than 18 cases have average results that are erratic through the forecast period and not significant. Forecasts of tropical cyclones whose environments were sampled (thick lines) were not improved more than those concurrent tropical cyclones whose environments were not sampled (thin lines), though the largest track forecast reductions at each forecast time are for sampled systems (Jangmi through 36 h, Sinlaku afterward). The smallest average forecast improvements (or largest degradations) were for Hanna through 84 h and for Ike thereafter. No relationship
between forecast error size and forecast improvement exists (Fig. 4). Dropwindsonde data obtained around tropical cyclones therefore has as much impact on track forecasts for nontargeted tropical cyclones as on those for the targeted tropical cyclones themselves.

Each tropical cyclone shown in Fig. 4 is discussed in chronological order, with emphasis on those cases with large track forecast changes but no environmental sampling of that particular system.

a. Hurricane Gustav

Four missions were conducted around Hurricane Gustav before its final landfall near Cocodrie, Louisiana, on 1 September; five other missions (some multiplane) were conducted in a nondeveloping system (TCS025) in the west Pacific during the lifetime of Gustav (Fig. 5). Average 1- to 4-day track forecast errors for Gustav were improved 10%–15% by the assimilation of the dropwindsonde data. The average track forecast improvements were small before the first Gustav mission, 3 Systems labeled TCSXXX were systems of interest to the TCS08 experiment that did not develop into tropical cyclones.
when data were collected in the west Pacific, and individual forecast differences shifted between forecast improvements and degradations, as expected (Zhang et al. 2003; Hodyss and Majumdar 2007).

Dropwindsonde data from individual G-IV missions are assimilated into 2 consecutive forecast cycles because the aircraft endurance is more than 8 h, and the GFS analyses are performed on a 6-h data assimilation cycle. About one-quarter of the dropwindsonde data are assimilated into the first cycle; both cycles are marked in Fig. 5 (and subsequent similar figures) as having had dropwindsonde data assimilated. Aberson (2010) showed that, in general, the cumulative forecast improvement from all the dropwindsonde data assimilated into both cycles is larger than that of just the few data assimilated into the first. The first cycles in which data from two Gustav missions were assimilated (1800 UTC 30 August and 1800 UTC 31 August) had substantial track forecast improvements.
from the assimilation of the dropwindsonde data, but their size decreases in the subsequent forecasts using all the accumulated dropwindsonde data. This seeming contradiction can be explained since, in all 4 forecasts, the operational and parallel runs both had small errors through 72 h (<200 km at 72 h) resulting in large relative, but small absolute, track forecast differences. The largest relative track forecast degradations during Gustav (0000 UTC 29 August and 0600 UTC 1 September) also occurred when both the operational and parallel runs produced forecasts with small errors, so the absolute differences were small.

b. Hurricane Hanna

Two missions were conducted around Hanna before its landfall near the North Carolina–South Carolina border (Fig. 6). Four other missions were conducted in the Atlantic around Gustav and 5 others in the west Pacific around two nondeveloping systems (TCS025 and TCS030) during the 6 days before these missions. The assimilation of the dropwindsonde data degraded Hanna track forecasts through 30 August, before the first Hanna mission. The two Hanna missions themselves led to large forecast improvements except in the short range. The cumulative impact on all Hanna forecasts was small (±4%) at all forecast times.

Impacts from the assimilation of distant observations before 31 August were negative since the operational forecast tracks were north and west of the parallel ones (e.g., Fig. 7). Hanna was located south of the subtropical ridge (Fig. 8a) at 0000 UTC 30 August, the initial time with the largest forecast degradation. Hurricane Ike was located to the east in the central Atlantic. A mission was conducted in the Gulf of Mexico and northwest Caribbean Sea around Hurricane Gustav, and another gathered dropwindsonde data in the west Pacific around the non-developing system TCS025. The northward bias appears
to be caused by a shortwave trough associated with the tail end of a cold front midway between Cape Cod and Bermuda that was forecast to amplify more in the operational than in the parallel run as represented by the cyclonic curvature in the forecast difference field (Fig. 8b). This feature weakened the west end of the subtropical ridge more in the operational run than in the parallel, allowing Hanna to move slightly northward. This feature appeared consistently in the operational runs starting on 27 August (not shown), before the first Gustav mission, leading to a consistent northward bias in the operational run. This likely caused the forecast degradations because it was the only feature consistent in every run during the forecast degradation period. The forecast degradations cannot be traced back to a particular initial difference between the operational and parallel runs, so the cause of this behavior is unknown.

Subsequent mixed impacts before the first Hanna mission (31 August–2 September) resulted from the assimilation of the dropwindsonde data alternately moving the operational forecast track to the right and left of the parallel forecast track. Initial differences between the two runs at each time are small near Hanna, but large deep-layer cyclonic and anticyclonic difference gyres in alternating runs are seen off the U.S. East Coast by about 2 days into the forecasts (not shown). These features originate in small initial differences over northeastern Canada that move southward during the forecast and change the steering flow over Hanna.

c. Hurricane Ike

Seven missions were conducted around Hurricane Ike between 6 and 11 September (Fig. 9). The last three Gustav missions, both Hanna missions, and one mission around a nondeveloping system in the west Pacific (TCS030) were conducted when Ike was east of the Leeward Islands. Ten other missions were conducted in the west Pacific (three in 16W and seven in Sinlaku) during the time when the environment of Ike was sampled, and three other missions (two in Sinlaku and one in Hagupit) were conducted in the west Pacific after Ike made landfall near Galveston, Texas, at 0700 UTC 13 September. The assimilation of the dropwindsonde data provided about 10% average track forecast improvements through 72 h, but degraded the average forecasts by almost 20% by 120 h (Fig. 4). The 1–3-day track forecasts were mostly improved before the Ike missions began. Substantial forecast degradations resulted after that time, except from 0600 to 1800 UTC 8 September.
At 0000 UTC 1 September, Ike was in the east Atlantic, part of a Rossby wave train (Brunet and Haynes 1996; Li and Fu 2006; Li et al. 2006) extending from Hurricane Gustav in the central Gulf of Mexico, to Tropical Storm Hanna north of Hispaniola, to a low-level circulation about 1000 km east of the Lesser Antilles, to Ike (Fig. 10a), and to another cyclonic circulation (not shown) that became Tropical Storm Josephine 3 days later. Shear induced by an upper-level low just north of the circulation between Hanna and Ike prevented that system from developing into a tropical cyclone. The parallel forecasts during this time had a northward bias, recurving Ike east of Bermuda (Fig. 11a). The operational forecasts maintained a closed circulation through 120 h, whereas the parallel runs forecast dissipation before or during recurvature (Fig. 11b).

The reason for these differences must be the assimilation of the dropwindsonde data obtained far from Ike, and two possibilities are investigated. Rossby wave dispersion that leads to wave trains similar to that shown here is correlated with tropical cyclone intensity (Li and Fu 2006), and the assimilation of synoptic dropwindsonde data causes analyzed tropical cyclones in the GFS to be more intense than if those data were not assimilated (Aberson 2010). Data collected on the leading edge (Hurricane Gustav) may have led to a large improvement in the track forecast of the tropical cyclone on the trailing edge (Ike) more than 5000 km away due to the dynamical connection along the Rossby wave train. Dropwindsonde data, almost all in the Gulf of Mexico, had been obtained thrice around Hurricane Gustav at 24-h intervals by 0000 UTC 1 September. The missions beginning 48 h before this time strengthened Gustav in the operational run (maximum sustained wind speed 52 kt; 1 kt = 0.5144 m s⁻¹) versus the parallel run (37 kt) and may have led to a strengthening of the Rossby wave train in the operational runs. This may have increased the dynamical relationship between Gustav and the trailing cyclonic circulations, leading to increased intensity of all four features in the operational runs. The model–forecast convection around the low pressure area between Hanna and Ike was stronger in the operational run than in the parallel run. This convection weakened the upper-level cold core low in the operational run more than in the parallel run. This resulted in the shear induced over Ike by this upper-level low in the operational run being less than in the parallel run. Ike was able to develop and remain stronger in the operational run than in the parallel run, in which the strong upper-level low sheared Ike, causing it to remain weak and recurve northward around the east side of the trough and dissipate. Supporting this
hypothesis is the fact that the assimilation of dropwindsonde data improved the Hanna forecast on 1 September (Fig. 6), and the Hanna (38 vs 35 kt) and Ike (25 vs 23 kt) intensities were higher in the operational analyses than in the parallel ones.

A second possibility is that tiny initial perturbations can amplify rapidly in areas of high convective available potential energy in a few hours (Zhang et al. 2003; Hodyss and Majumdar 2007; Aberson 2002, 2010). The cyclonic circulations that make up the Rossby wave train were convectively active tropical cyclones. The initial dropwindsonde data impact at 0000 UTC 1 September was spread throughout the Atlantic (Fig. 10b) in these convectively active regions, though it is small around Hanna. The average impact is likely to be very small, and some forecasts were improved and others degraded by the assimilation of the dropwindsonde data.

The initial condition difference between the operational and parallel runs initialized before any dropwindsonde data from Gustav missions were assimilated into the model (1200 UTC 29 August) is investigated to test which factor may be most important. Three missions in the west Pacific around the system designated TCS025 had already been conducted. The differences in the initial condition must result from these missions. Figure 12 shows that impacts from these missions were spread throughout the Atlantic but maximized near cyclonic circulations, suggesting that the impacts were organized in convective regions before the Rossby wave train developed. This does not preclude the possibility that the Gustav data also impacted the forecast through the Rossby wave train dynamics since it is impossible to separate the two effects.
A second period of consistent 1–3-day track forecast improvements due to the assimilation of dropwindsonde data occurred from 5 to 6 September (Fig. 13). This period coincided with a 2-day lull in environmental sampling, so the impact would likely be a residual from missions that occurred prior to 0000 UTC 4 September. The Rossby wave train had dissipated (Fig. 14) by 0000 UTC 6 September, when the largest consistent track forecast improvements occurred. Tropical Storm Hanna was approaching landfall near the North Carolina–South Carolina border; Hurricane Ike was moving westward north of Puerto Rico, and Tropical Depression Josephine was weakening due to shear from an upper-level low in the far east tropical Atlantic. The likely reason for these forecast improvements is that the positive vorticity region at the tail end of a front to the northeast of Ike was stronger in the operational than in the parallel analysis (Fig. 15a). This feature moved westward behind Ike, south of the subtropical high (Fig. 15b). This contrasts the Hanna forecasts in which a similar feature moved eastward to the north of the subtropical ridge passing the longitude of the tropical cyclone. Whereas the feature in the Hanna case weakened the ridge to the north leading to a northward bias for Hanna, this feature increased the northerly flow to the west of Ike leading to a southward track bias. These impacts that are distant from the sampling region would be expected to have no bias, suggesting that the model overamplifies these convective subtropical features.

d. Tropical Storm Josephine

No missions were conducted around Tropical Storm Josephine during its lifetime in the east Atlantic; two missions were conducted around Hanna in the west Atlantic, and one around a nondeveloping system (TCS030) in the west Pacific (Fig. 16). These distant missions led to 20%–25% track forecast improvements through 48 h, and most individual impacts were positive from 2 to 5 September. The largest forecast improvement, at 0000 UTC 4 September, is representative of others in Josephine (Fig. 17). Josephine was moving toward the west beneath a strong subtropical ridge, and an upper-level low was located to its northwest (Fig. 18). The assimilation of the dropwindsonde data caused the upper-level low to be stronger in the operational than in the parallel run (Fig. 17) and kept Josephine within the high shear zone near the low. The impacts cannot be traced back to a particular initial condition difference, so are likely due to the remote data.

e. Typhoon Sinlaku

Typhoon Sinlaku provided some of the largest forecast track differences due to the assimilation of dropwindsonde data. A total of 18 missions were conducted in and around Sinlaku from 9 to 21 September, including 2 missions after Sinlaku transitioned to an extratropical cyclone (Fig. 19). Average forecast improvements ranged from about 5% at 24 h to more than 25% from 60 to 120 h.
Early in the Sinlaku life cycle, two other missions were conducted in the west Pacific in Tropical Depression 16W, and four others were conducted in the Atlantic around Hurricane Ike; two other missions were conducted on 13 and 15 September around Typhoon Hagupit. The early missions (through 12 September) provided improved track forecasts except at 24 h. The Sinlaku mission on 14 September resulted in degraded forecasts, and subsequent missions had small positive to mixed results.

f. Typhoon Hagupit

Three missions were conducted in and around Typhoon Hagupit (Fig. 20); the first (not shown in Fig. 20) was conducted 2 days before the system became a tropical depression, and two others occurred within 72 h of landfall in south China. Seven missions were conducted to the north around Sinlaku between the Hagupit missions. The average Hagupit track forecasts were improved by up to 15% through 48 h (Fig. 4). Because most Hagupit forecasts were initialized between the first and second missions, the impact is likely due to the missions conducted around Sinlaku during that period.

The reason for the lack of forecasts extending past 2 or 3 days (Fig. 20) is that the parallel runs forecast Hagupit to dissipate prematurely, like in the early Ike forecasts. The assimilation of dropwindsonde data around sampled tropical cyclones cause them to be more intense in operational runs than in parallel ones (Aberson 2010), but missions around Hagupit were conducted toward the end of the period, so the dropwindsonde data obtained around Sinlaku are the reason for the initial intensity increase. Sinlaku was undergoing extratropical transition almost due north of Hagupit, and a strong subtropical ridge separated the two systems (Fig. 21). No dynamical connection between the two systems...
A small difference between the operational and parallel runs allowed the former to have a higher initial intensity than the latter (19 vs 17 kt), allowing Hagupit to remain in the forecast (Fig. 22a). This small increment amplified in time, first slowly (Fig. 22b), then rapidly (Fig. 22c) as the analysis cycle continued. The residual impact from missions around Sinlaku allowed for the better initial representations of Hagupit in the operational run than in the parallel, thus improving the forecasts.

g. Typhoon Jangmi

Aircraft flew Typhoon Jangmi from the day before genesis occurred on 24 September through its extratropical transition (Fig. 23). The impact of the first missions on the first three forecasts after genesis was largely positive, but turned negative by 1800 UTC 25 September. Missions beginning 27 September mostly degraded the track forecasts. The last two missions occurred during the extratropical transition phase.

h. Hurricane Kyle

No surveillance missions were flown around Hurricane Kyle in the Atlantic; a series of missions were conducted in the west Pacific around Jangmi during this time (Fig. 24). The average impact was positive through 3 days, with 15%–30% track forecast improvements due to the assimilation of dropwindsonde data. Five forecasts, those from 0600 UTC 25 September to 24 h later, had large differences, the first three having large forecast improvements, the remainder mainly degradations. One surveillance mission was conducted during this time, at the beginning of the period around Jangmi in the west Pacific. NOAA aircraft released numerous dropwindsondes in both Kyle and the nontropical system that developed from the occluded low off the Carolina coast in research missions every 12 h from around 0000 UTC 24 September through 1800 UTC 27 September. Since many of these dropwindsonde data were outside the
111.1-km radius from the center, and data within this radius are rejected by the GSI, the assimilation of these data caused the forecast differences. This result shows the importance that regular reconnaissance missions can have on numerical track forecasts.

The impacts during a series of three forecasts, each separated by 6 h (1800 UTC 25 September–0600 UTC 26 September, with a NOAA P-3 mission taking place around the middle synoptic time), alternated from a large forecast improvement to a degradation and finally to a mixed result (Fig. 25). The initial differences between the operational and parallel runs just north of Kyle alternate between an anticyclonic increment at 1800 UTC 25 September (Fig. 26a), to a cyclonic increment 6 h later (Fig. 26b), and back to an anticyclonic increment that was weaker than the earlier one 6 h later (Fig. 26c). This allowed the operational run to alternate between a slow, then fast, and then slow northward motion, leading to the large positive, then negative, then mixed forecast results from the three missions.

The ultimate reason for the differences in the impact with time is unknown, though it is troubling that the data within the two systems degraded the forecast into which they were assimilated. Data from a previous P-3 mission centered around 1200 UTC 25 September also improved that forecast, and the impact of that mission remained
6 h later (Aberson 2010). These earlier data suggested that the extratropical low approaching the Carolina coast was stronger than the first guess. Data from the subsequent mission sampled only the east side of the system as it was making landfall, and suggested a weaker system than in the first guess. This westerly increment seems to have extended offshore to the north of Kyle, suggesting a stronger midlatitude trough and faster northerly motion. This westerly increment had moved northward away from Kyle by 6 h later. Kyle was then much stronger in the operational than the parallel run (maximum sustained winds 38 vs 26 kt). The easterly winds to the north of Kyle were thus stronger in the operational run than in the parallel, serving to amplify the ridge to the north and keeping Kyle farther to the south.

5. Conclusions

An observing system experiment to test global dropwindsonde data impact from 26 August to 2 October 2008, during which multiple missions were conducted around tropical cyclones in the Atlantic and west Pacific, is presented. Additional unsampled tropical cyclones in those regions, as well as others in the east Pacific and Indian Oceans provide a large number of cases to examine the dropwindsonde data impact on tropical cyclone tracks globally for the first time. The large number of tropical cyclone cases (240 at 12 h decreasing to 136 at 120 h) is larger than in previous studies.

The assimilation of dropwindsonde data provide global improvements to tropical cyclone track forecasts of about 10% through 72 h, but decreasing at longer forecast lead times. The improvements to the west Pacific tropical cyclone track forecasts are generally smaller than the global average through 72 h and larger afterward. Atlantic tropical cyclone track forecast improvements are similar to those shown in Aberson (2010), generally decreasing with increasing lead time. Impacts on the east Pacific tropical cyclone track forecasts are comparable to those in the basins with aircraft data, despite the lack of dropwindsonde observations there, suggesting a global impact from the local dropwindsonde observations.

The largest error reductions at each forecast lead time are in the west Pacific (Jangmi through 36 h, Sinlaku thereafter), with average forecast error reductions for both ranging from 20% to 35%. Smallest positive (or largest negative) impacts are in the Atlantic for Hurricane Hanna through 84 h and Hurricane Ike thereafter, with Ike experiencing large forecast degradations (15%–20%) from 108 to 120 h. Both Kyle and Josephine in the Atlantic showed large forecast improvements (10%–30% through 84 h) despite not having been sampled by dropwindsondes, further suggesting remote impacts from the dropwindsonde observations.

The only differences between the two runs in this study are the data that were assimilated (either all dropwindsonde data or no dropwindsonde data globally) and the computer on which the GFS was run. Differences between the two runs must be due to one or both factors. Previous studies have detailed the dropwindsonde data impact on the forecasts for the tropical cyclones that were sampled, so here, cases with large impacts but no sampling are examined. Discerning which of the two factors is dominant is not possible because most impacts are remote from the dropwindsonde observations. The assimilation of dropwindsonde data
are likely to have a positive average impact on all tropical cyclone track forecasts globally, not just on those tropical cyclones that are targeted for forecast track improvement.

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