Diagnosing Initial Condition Sensitivity of Typhoon Sinlaku (2008) and Hurricane Ike (2008)

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(Manuscript received 21 October 2010, in final form 28 March 2011)

ABSTRACT

The response of Weather Research and Forecasting (WRF) model predictions of two tropical cyclones to perturbations in the initial conditions is investigated. Local perturbations to the vorticity field in the synoptic environment are created in features considered subjectively to be of importance to the track forecast. The rebalanced analysis is then integrated forward and compared with an unperturbed “control” simulation possessing similar errors to those in the corresponding operational model forecasts. In the first case, Typhoon Sinlaku (2008), the premature recurvature in the control simulation is found to be corrected by a variety of initial perturbations; in particular, the weakening of an upper-level low directly to its north, and the weakening of a remote short-wave trough in the midlatitude storm track. It is suggested that one or both of the short waves may have been initialized too strongly. In the second case, the forecasts for Hurricane Ike (2008) initialized 4 days prior to its landfall in Texas were not sensitive to most remote perturbations. The primary corrections to the track of Ike arose from a weakening of a midlevel ridge directly to its north, and the strengthening of a short-wave trough in the midlatitudes. For both storms, the targets selected by the ensemble transform Kalman filter (ETKF) were often, but not always, consistent with the most sensitive regions found in this study. Overall, the results can be used to retrospectively diagnose features in which the initial conditions require improvement, in order to improve forecasts of tropical cyclone track.

1. Introduction

In the environment of tropical cyclones (TCs), the evolution of features including adjacent subtropical ridges, a midlatitude trough, or a nearby cyclonic circulation may influence the motion and behavior of the TC. Early studies focused on the dynamical processes that govern TC motion, beginning with investigations of barotropic processes (reviewed in Elsberry 1995), and potential vorticity (PV) in a baroclinic environment (Shapiro 1992; Wu and Emanuel 1993; Molinari et al. 1998; Wu and Wang 2000). Additionally, piecewise PV inversion (Davis and Emanuel 1991) was employed to diagnose the steering flow and the interaction between the TC and its environment (Wu and Emanuel 1995a,b). It was found that the balanced flows deduced via the separation of PV fields were useful in interpreting TC motion.

Recently, attention has turned to investigating errors in numerical forecasts of TC motion that arise due to inaccuracies in their initial conditions. To explore this, several objective sensitivity methods, such as singular vector (Peng and Reynolds 2006; Chen et al. 2009; Kim and Jung 2009), adjoint-derived sensitivity steering vector (Wu et al. 2007), and ensemble sensitivity (Torn and Hakim 2008), have been devised. These methods have been used to identify locations in which to target observations during field campaigns such as The Observing System Research and Predictability Experiment (THORPEX) Pacific Asian Regional Campaign (T-PARC; Reynolds et al. 2010). Other methods such as the ensemble transform Kalman filter (ETKF; Majumdar et al. 2011) investigate the sensitivity of TC forecasts to the assimilation of observations. Sensitivity guidance products provided by these respective methods
often exhibit different characteristics for common cases (Majumdar et al. 2006; Wu et al. 2009).

These objective initial condition sensitivity methods are also only perfect when linear dynamics are obeyed, and if the data assimilation scheme (if assumed) is perfect. In this paper, we employ a more direct approach to investigate the means by which TC forecasts may be modified via changes to the analysis, by subjectively perturbing the initial conditions in specified environmental features and integrating the forecast model forward. Initial perturbations are created via the amplification or weakening of relative vorticity within a chosen area and layer in the synoptic environment of the TC, followed by a rebalancing of the newly modified field. The primary goal of the study is to diagnose the primary initial condition sensitivities when full-field. The primary goal of the study is to diagnose the primary initial condition sensitivities when full-field.

In section 2, the regional modeling framework and vorticity perturbation technique are presented. In sections 3 and 4, the applications of this technique to Tropical Cyclones Sinlaku and Ike, respectively, are presented, followed by concluding remarks in section 5.

2. Methodology

a. Modeling framework

Version 3.1.1 of the regional Advanced Research Weather Research and Forecasting model (WRF-ARW) is employed in this paper. A single, fixed grid with a horizontal resolution of 21 km and 41 vertical levels is used. The domains for the two TC cases are chosen such that all synoptic targets are included: 8946 km × 7056 km for Typhoon Sinlaku and 6510 km × 5880 km for Hurricane Ike. The following physics options are used: Rapid Radiative Transfer Model (RRTM) longwave radiation (Mlawer et al. 1997; Iacono et al. 2000), Dudhia shortwave radiation (Dudhia 1989), WRF Single-Moment (WSM) six-class microphysics (Dudhia et al. 2008), and the Mellor–Yamada–Janjic (MYJ) boundary layer scheme (Mellor and Yamada 1982; Janjic 1990). A second-order diffusion scheme is employed, and no damping is used.

Several global models were initially examined for use as initial and boundary conditions. An intercomparison between the 2008 versions of the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS), the Navy Operational Global Atmospheric Prediction System (NOGAPS), and the European Centre for Medium-Range Forecasts (ECMWF) model revealed that the ECMWF produced the most realistic vortex initialization. Therefore, twice-daily 1° × 1° horizontal resolution ECMWF analyses are used to provide initial and boundary conditions for the WRF domain in this study. For each TC case, a “control” (nonperturbed) simulation, and an array of “perturbed” simulations in which the initial conditions are modified by local, balanced perturbations of vorticity in the synoptic environment, are integrated out to 5 days. The “sensitivity” to a given location is then interpreted as the change in TC track associated with a particular vorticity perturbation.

b. Vorticity perturbation technique

The modification to the initial conditions is achieved by first perturbing the relative vorticity field within a local cylinder of radius R and, then, rebalancing the flow by solving for the nondivergent streamfunction followed by the geopotential. While it is desirable to use a full piecewise potential vorticity inversion technique such as that of Davis (1992), the method employed here is computationally simpler and follows the vorticity removal and inversion method of Davis and Low-Nam (2001), which has been widely used as a component of the fifth-generation National Center for Atmospheric Research–Pennsylvania State University (NCAR–Penn State) Mesoscale Model (MM5) system. In this study, the technique is designed to ensure that smooth, balanced changes to the analysis are created.

The location and radius of perturbation, the pressure levels \(p_{\text{top}}\) and \(p_{\text{bot}}\) between which the perturbation is applied, and the multiplicative factor \(\alpha_{\text{max}}\) applied to the vorticity value at the perturbation center are all specified subjectively. The perturbation magnitude \(\alpha(r, p)\) decreases linearly outward with radius \(r\) from the point \((0, p_{\text{mean}})\) as follows:
where \( p_{\text{mean}} \) is the mean of \( p_{\text{bot}} \) and \( p_{\text{top}} \). Therefore, \( \alpha(r, p) = \alpha_{\text{max}} \) at the point \((0, p_{\text{mean}})\). The perturbation technique is fundamentally identical to the NCAR vortex removal technique (Davis and Low-Nam 2001), with two additional modifications. First, the inclusion of \( \alpha_{\text{max}} \) allows for incremental, rather than complete, removal (or increases) of vorticity. Second, the perturbation scales linearly to zero at a user-specified \( p_{\text{top}} \) and \( p_{\text{bot}} \). This modification allows for the perturbation of features that exist through a limited depth of the troposphere, such as upper-level lows or surface anticyclones. The new relative vorticity \( \xi_1 \) is then expressed as a sum of the original relative vorticity \( \xi_0 \) and the perturbation relative vorticity \( \xi' \):

\[
\xi_1 = \xi_0 + \xi' = \left[1 + \alpha(r, p)\right]\xi_0. \tag{2}
\]

The streamfunction is recovered via inversion of the Laplacian operator in \( \psi' = \nabla^2 \xi' \) through the use of a successive overrelaxation technique (Tannehill et al. 1997). The nondivergent wind perturbation \( \mathbf{v}' = k \times \nabla \psi' \) is then computed and added to the initial wind field, while the divergent component remains unperturbed. The geopotential field is then adjusted via geostrophic balance, and the temperature is finally adjusted through hydrostatic balance.

An example of the perturbed fields is illustrated in Fig. 1. An upper-layer (500–200 hPa) negative vorticity perturbation of strength \( \alpha_{\text{max}} = -0.23 \) (Fig. 1a) is introduced in order to weaken a strong midlatitude short wave. The resulting modification to the vorticity field is local to the perturbation (Fig. 1b), with the largest vorticity perturbation value situated off center due to the value of the vorticity being significantly larger at adjacent locations. While the perturbation itself \( \alpha(r, p) \) is a circle on a height surface, the perturbed vorticity \( \xi_1 \) is not circular (Fig. 1b), due to the fact that it is a function of both \( \alpha(r, p) \) and the initial vorticity \( \xi_0 \). The changes to the 500-hPa geopotential height (Fig. 1c) and deep-layer (850–200 hPa) mean velocity fields (Fig. 1d) extend farther outward, with wind perturbations dropping below 1 m s\(^{-1}\) 1000 km from the perturbation center. The initial perturbations are qualitatively similar in shape and spatial extent to those produced by the assimilation of an observation in a scheme that permits quasi-isotropic error covariance information, such as the NCEP Gridpoint Statistical Interpolation scheme (Kleist et al. 2009). While the vorticity perturbation is constrained to be within radius \( R \), due to the inversion of the Laplacian operator over the model domain, small initial wind (\( V \)) perturbations remain at remote distances. Vorticity perturbations are chosen such that the maximum \( V \) perturbation in the vicinity of the tropical cyclone is 1 m s\(^{-1}\) or less, and additional diagnoses are conducted to determine that the most significant contribution to the track forecast arises from the vicinity of the perturbation center and not from the remote initial perturbation near the TC. It is also worth noting that “data impact” computations using operational data assimilation can produce initially small, rapidly growing perturbations remote from the location of the observational data (Hodys and Majumdar 2007), leading to upscale growth (Zhang et al. 2003). Small initial perturbations may influence track forecasts of TCs, with the long-wave pattern being modified significantly even after 2 days (Aberson 2008; Brennan and Majumdar 2011).


a. Synopsis and selection of targets

Typhoon Sinlaku (2008) posed a series of forecasting challenges from its genesis through to recurvature and extratropical transition. In this paper, we focus on forecasts initialized at 0000 UTC 10 September 2008, at which time Sinlaku had been declared by the Joint Typhoon Warning Center as a typhoon with maximum sustained winds (averaged over 10 min) of 90 kt (1 kt = 0.5144 m s\(^{-1}\)), meandering slowly northward and posing a potential threat to Taiwan (Fig. 2a). Sinlaku is situated in between two large deep-layer anticyclones: one over China and the other over the western North Pacific Ocean (Fig. 2b). The lack of a dominant steering flow contributed to the large spread in the 5-day ECMWF ensemble forecasts of Sinlaku (Fig. 2c). Several of the deterministic forecasts produced a 5-day forecast over 500 km to the east of the actual track, with recurvature occurring by 4 days, 2 days too early. The WRF control simulation initialized from the ECMWF analysis produced a forecast track with similar timing and location errors as the operational models. After

\[
a(r, p) = \begin{cases} 
2 \frac{R - r}{R} \frac{p - p_{\text{top}}}{p_{\text{bot}} - p_{\text{top}}} \alpha_{\text{max}}, & r \leq R, \quad p_{\text{top}} \leq p \leq p_{\text{mean}} \\
2 \frac{R - r}{R} \frac{p_{\text{bot}} - p}{p_{\text{bot}} - p_{\text{top}}} \alpha_{\text{max}}, & r \leq R, \quad p_{\text{mean}} \leq p \leq p_{\text{bot}} \\
0, & r > R, \quad p \leq p_{\text{top}}, \text{ or } p > p_{\text{bot}}. 
\end{cases} \tag{1}
\]
a correctly predicted slow track over the first 2 days (with a 2-day error of only 44 km), the control forecast diverged considerably from the best track over the following 3 days with an erroneously strong northward component (Fig. 2d). Between 2 and 5 days, the forecast error in the control run grew almost linearly at 200 km day$^{-1}$, culminating in a 5-day error of 644 km.

The locations for the vorticity perturbations were selected within features in the synoptic environment of Sinlaku that may be expected to influence the track. The locations (designated with an S for Sinlaku) include a remote midlatitude short-wave trough to the north-northwest of Sinlaku (S1), a smaller upper-level short wave nearby to the north (S2), a low-level monsoon trough over Vietnam and Cambodia to the west-southwest (S3), and the decaying Tropical Storm 16W, just southwest of Japan (S4) (Fig. 3). The large upper-level trough within which S1 is selected lies in between two large ridges in an amplified long-wave pattern. The center of the perturbation for S1 is selected to be at the southern end of a short wave over southeast Russia and Mongolia, with a radius of perturbation $R = 600$ km. This radius is similar to the radius of curvature in the base of the trough, beyond which the flow becomes dominated by the surrounding ridges (Fig. 3a). Target S2 is a smaller upper-level trough that becomes cut off from the jet 2 days prior to the initial time, only to rejoin the jet 36 h later. To restrict the perturbation to the vicinity and scale of S2, $R$ is reduced to 400 km. For the lower-tropospheric targets S3 and S4, $R$ is set to 500 and 400 km respectively, consistent with the sizes of their circulations. The maximum vorticity in the low-level monsoon trough associated with S3 is smaller than that for the other targets (Fig. 3b). Target S4 is associated...
with high vorticity in the lower troposphere over a small area spanning Tropical Storm 16W. These four targets all lie in cloudy areas (Fig. 1). A fifth location (“SE”) downstream of target S1, based on guidance from the ETKF strategy, is also examined (Fig. 3a). Finally, a region 200 km downstream of Sinlaku is selected to examine the sensitivity of the TC to a local perturbation that is not associated with a distinct synoptic feature. This target is designated SC (Fig. 3b).

b. Sensitivity to perturbations

The choice of the multiplicative factor $\alpha_{\text{max}}$ is subjective, and it depends on the type of feature to be perturbed. First, perturbations with $\alpha_{\text{max}} = \pm 0.75$ are selected. Although the magnitudes of these perturbations are larger than typical inaccuracies in an operational analysis, they are initially created to investigate the gross characteristics of the sensitivity. Next, $\alpha_{\text{max}}$ is incrementally reduced for perturbation S2, in order to identify a state in which the perturbation may compensate for local errors in the model analysis and allow for the successful replication of the TC’s best track. To compare the effects of perturbing two targets (S1 and S2) with a consistent initial wind perturbation $|V'|_{\text{max}}$, a new perturbation of $\alpha_{\text{max}} = \pm 0.23$ is then applied to S1. Finally, for SC, a $\pm 0.16$ perturbation is applied in order to produce a $V$ perturbation of average magnitude equal to 1 m s$^{-1}$ within a 300-km radius of the TC. A summary of targets and corresponding values of $\alpha_{\text{max}}$ is given in Table 1.

1) S1: MIDLATITUDE TROUGH

To examine the sensitivity and the robustness of the perturbation technique, a range of positive and negative vorticity perturbations is selected. Target S1 is perturbed using $\alpha_{\text{max}} = \pm 0.75$ and $\pm 0.23$, generating...
maximum vertically averaged deep-layer (850–200 hPa) wind perturbations of 15.6 and 4.9 m s\(^{-1}\), respectively, at the target, and 0.6 and 0.2 m s\(^{-1}\), respectively, within 300 km of the center of Sinlaku. The WRF forecast track of Sinlaku is found to be highly sensitive to the perturbations with \(\alpha_{\text{max}} = \pm 0.75\) (Fig. 4a). The substantial weakening of the S1 trough (\(\alpha_{\text{max}} = -0.75\)) produces a track well to the left of the best track, with an initial landfall in southern Taiwan and a second landfall in China. On the other hand, the strengthening of the S1 trough (\(\alpha_{\text{max}} = +0.75\)) acts to accelerate Sinlaku toward the north-northeast. For both positive and negative perturbations, the 5-day forecast differs from the control run by over 1000 km.

A perturbation of \(\alpha_{\text{max}} = -0.23\) corrects the premature recurvature and replicates the actual track almost perfectly. This modest weakening to the S1 trough produces an initial negative perturbation of meridional wind (\(\nu\)) on the east side of the trough corresponding to a weakening of the southerly wind component, and a positive \(\nu\) perturbation on the west side corresponding to a weakening of the northerly wind component (Figs. 5a and 1d). The weakening of the S1 trough strengthens the eastern periphery of the anticyclone over China very slightly, resulting in slightly stronger northerly wind to the west of Sinlaku (Figs. 5b–d). Concurrently, weaker southerly wind on the east side of S1 propagates southward with time, away from the

### Table 1. Summary of cases for Typhoon Sinlaku initialized on 0000 UTC 10 Sep 2008. Columns correspond to target name (target), maximum vorticity amplification factor (\(\alpha_{\text{max}}\)), radius of perturbations (\(r_{\text{per}}\), km), distance between the perturbation and the TC (distance, km), the normalized ETKF sensitivity (ETKF), the maximum magnitude of the 850–200-hPa vertically averaged wind perturbation at the target (\(|V'_{\text{max}}|\) at target) and at the TC (\(|V'_{\text{max}}|\) at TC, m s\(^{-1}\)), and the distance (km) between the perturbed and the control tracks, for 48- and 120-h forecasts.

| Target | \(\alpha_{\text{max}}\) | \(r_{\text{per}}\) (km) | Distance (km) | ETKF | \(|V'_{\text{max}}|\) at target (m s\(^{-1}\)) | \(|V'_{\text{max}}|\) at TC (m s\(^{-1}\)) | 48-h \(\Delta\text{track}\) (km) | 120-h \(\Delta\text{track}\) (km) |
|--------|-----------------|----------------|--------------|------|--------------------------|----------------|----------------|----------------|
| S1     | -0.75           | 600            | 3200         | 0.65 | 15.6                     | 0.6            | 220            | 1086           |
| S1     | -0.23           | 400            | 3200         | 0.65 | 4.9                      | 0.2            | 60             | 577            |
| S2     | -0.75           | 400            | 1200         | 0.79 | 4.9                      | 0.6            | 246            | 1108           |
| S2     | -0.55           | 400            | 1200         | 0.79 | 3.6                      | 0.4            | 188            | 905            |
| S2     | -0.25           | 400            | 1200         | 0.79 | 1.6                      | 0.2            | 80             | 808            |
| S2     | -0.15           | 400            | 1200         | 0.79 | 1.0                      | 0.1            | 53             | 366            |
| S3     | -0.75           | 500            | 2300         | 0.92 | 4.9                      | 0.7            | 107            | 464            |
| S4     | -0.75           | 400            | 2500         | 0.56 | 3.1                      | 0.1            | 84             | 771            |
| SC     | -0.16           | 500            | 200          | 0.87 | 0.6                      | 0.6            | 27             | 38             |
| SE     | -0.75           | 600            | 3400         | 0.89 | 7.3                      | < 0.1          | 38             | 362            |
initial perturbation, resulting in weaker southerly wind to the east of Sinlaku. The net effect of these negative $v$ anomalies both east and west of Sinlaku is to slow the northward propagation of the cyclone. The short-term track forecast was not substantially modified (and was in fact degraded by 23 km at 48 h) due to the perturbation. From 60 h, the modification to the track is consistent with the onset of bifurcation between the track forecasts in the control and perturbed simulations during this period, with the perturbed track remaining to the south of the control (Fig. 4a). While there is a significant modification to the meridional component of the wind in the environment of Sinlaku, the modification to the zonal component is relatively small, as expected, since the zonal wind in this region is weak. However, Sinlaku travels farther west in the perturbed simulation than in the control, since it remains sufficiently remote from the short wave to its north to avoid recurvature. Its

![Figure 4](image)

**FIG. 4.** The 5-day WRF track simulations initialized 0000 UTC 10 Sep 2008 for perturbations at targets (a) S1 and (b) S2. Each dot represents a 1-day forecast increment.

![Figure 5](image)

**FIG. 5.** Colors show the meridional wind difference (m s$^{-1}$) between the perturbed ($a_{\text{max}} = -0.23$) and control WRF simulations for (a) 0, (b) 12, (c) 24, (d) 36, (e) 48, and (f) 60 h. A positive (negative) value implies that the positive meridional component in the perturbed simulation is higher (lower) than that in the control simulation. Vectors show the 850–200-hPa-layer mean wind in the control simulation. The location of Sinlaku at the corresponding time is indicated by the TC symbol.
continued slow westward motion, resulting in a 5-day track forecast error of just 113 km (compared with 644 km in the control run), is likely due to a combination of the weaker southeasterly flow in the Pacific ridge and the beta drift of Sinlaku.

In contrast, when the trough at S1 is strengthened ($\alpha_{\text{max}} = +0.23$), the opposite evolutionary pattern occurs. As the positive meridional wind perturbation on the east side of the trough extends southward, Sinlaku accelerates northward around the western periphery of the strengthened Pacific ridge. In doing so, Sinlaku recurs even earlier in the perturbed simulation than the control, with a 5-day error exceeding 1000 km. Similar results have been found for perturbations of different strengths, with larger perturbations producing proportionally greater deviations to the track. A summary of track errors of the control and perturbed simulations is given in Table 2.

2) S2: UPPER-LEVEL LOW

Target S2 is perturbed using $\alpha_{\text{max}} = \pm 0.75$, $\pm 0.55$, $\pm 0.25$, and $\pm 0.15$, generating maximum changes to the 850–200-hPa wind of 4.9, 3.6, 1.6, and 1.0 m s$^{-1}$, respectively, at the target, and initial wind perturbations of 0.6, 0.4, 0.2, and 0.1 m s$^{-1}$ at Sinlaku. A wide spreading of 5-day track forecasts for Sinlaku results from these eight perturbations (Fig. 4b). All simulations in which the short wave is strengthened lead to an earlier recurvature, and a track even farther from the best track than that for S1 at 24 h, possibly due in part to the relative proximity of S2 to Sinlaku compared with S1. At later times, the weakening of the southerly wind on the west side of the Pacific ridge remains, leading to a weaker northward motion of Sinlaku than in the control simulation (Figs. 6d–f). As is the case with the weakening of the S1 trough, the recurvature of Sinlaku is again delayed, leading to a forecast track that drifts farther westward with a 5-day track forecast error of only 200 km. Again, there is a minimal short-term deterioration of the forecast track, but this becomes overwhelmed by the improvement beyond 2 days as the influence of the perturbations to the synoptic environment takes over.

3) S3 AND S4: LOWER-LEVEL PERTURBATIONS

Despite the fact that both low-level targets (with $\alpha_{\text{max}} = \pm 0.75$) have a minimal vorticity signature at the upper levels and are of relatively small spatial scale, the simulation of Sinlaku is sensitive to small perturbations in these regions (Figs. 7a and 7b). In the 850–700-hPa layer wind analysis (not shown), a broad region of southwesterly winds associated with S3 appears to modify the track of Sinlaku. In weakening the monsoon trough, these winds subsequently weaken with negative perturbations of zonal and meridional winds generated on the east side of the trough. This signal weakens the environmental forcing that supports the northeastward motion of Sinlaku, resulting in a track that is not as far to the east or north as the control. Despite a small recurring short-term deterioration of the track forecast, the west side of the Pacific remains, leading to a 5-day track forecast error of just 113 km (compared with 644 km in the control run), is likely due to a combination of the weaker southeasterly flow in the Pacific ridge and the beta drift of Sinlaku.

In contrast, when the trough at S1 is strengthened ($\alpha_{\text{max}} = +0.23$), the opposite evolutionary pattern occurs. As the positive meridional wind perturbation on the east side of the trough extends southward, Sinlaku accelerates northward around the western periphery of the strengthened Pacific ridge. In doing so, Sinlaku recurs even earlier in the perturbed simulation than the control, with a 5-day error exceeding 1000 km. Similar results have been found for perturbations of different strengths, with larger perturbations producing proportionally greater deviations to the track. A summary of track errors of the control and perturbed simulations is given in Table 2.

**Table 2.** First two columns are as in Table 1. Boldface shows errors (in km) of the control forecast for Typhoon Sinlaku, initialized on 0000 UTC 10 Sep 2008. The remaining numbers show the improvements (−) or degradations (+) to the control forecast (km), computed as the track forecast error of the perturbed simulation minus that of the control simulation. Values in italics (and underlined) correspond to improvements over 100 (200) km.

<table>
<thead>
<tr>
<th>Target</th>
<th>$\alpha_{\text{max}}$</th>
<th>48 h</th>
<th>60 h</th>
<th>72 h</th>
<th>84 h</th>
<th>96 h</th>
<th>108 h</th>
<th>120 h</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTRL</td>
<td></td>
<td>159</td>
<td>129</td>
<td>110</td>
<td>100</td>
<td>108</td>
<td>110</td>
<td>119</td>
</tr>
<tr>
<td>S1</td>
<td>$-0.75$</td>
<td>$+185$</td>
<td>$+179$</td>
<td>$+95$</td>
<td>$+100$</td>
<td>$+120$</td>
<td>$-23$</td>
<td>$-95$</td>
</tr>
<tr>
<td>S1</td>
<td>$+0.23$</td>
<td>$+26$</td>
<td>$-15$</td>
<td>$-146$</td>
<td>$-220$</td>
<td>$-224$</td>
<td>$-378$</td>
<td>$-531$</td>
</tr>
<tr>
<td>S2</td>
<td>$-0.75$</td>
<td>$+212$</td>
<td>$+225$</td>
<td>$+150$</td>
<td>$+153$</td>
<td>$+120$</td>
<td>$-76$</td>
<td>$-96$</td>
</tr>
<tr>
<td>S2</td>
<td>$-0.55$</td>
<td>$+159$</td>
<td>$+129$</td>
<td>$+68$</td>
<td>$+48$</td>
<td>$+19$</td>
<td>$-206$</td>
<td>$-311$</td>
</tr>
<tr>
<td>S3</td>
<td>$-0.25$</td>
<td>$+60$</td>
<td>$-15$</td>
<td>$-119$</td>
<td>$-160$</td>
<td>$-174$</td>
<td>$-362$</td>
<td>$-444$</td>
</tr>
<tr>
<td>S4</td>
<td>$-0.15$</td>
<td>$+36$</td>
<td>$-46$</td>
<td>$-91$</td>
<td>$-108$</td>
<td>$-142$</td>
<td>$-274$</td>
<td>$-355$</td>
</tr>
<tr>
<td>SC</td>
<td>$-0.16$</td>
<td>$+15$</td>
<td>$-35$</td>
<td>$-19$</td>
<td>$-38$</td>
<td>$0$</td>
<td>$+18$</td>
<td>$+38$</td>
</tr>
<tr>
<td>SE</td>
<td>$-0.75$</td>
<td>$+36$</td>
<td>$-35$</td>
<td>$-55$</td>
<td>$-93$</td>
<td>$-160$</td>
<td>$-246$</td>
<td>$-363$</td>
</tr>
</tbody>
</table>
long-term track forecast improves such that the 5-day error decreases to only 205 km. The opposite effect occurs when the monsoon trough S3 is strengthened. Upon weakening S4 (Tropical Storm 16W), the subtropical ridge over the western Pacific is allowed to build over the first 2 days, with the resulting increased deep-layer easterlies on the southern side of the ridge forcing Sinlaku farther west and avoiding recurvature. The forecast track error is consistently lower than that of S3 (172 km at 5 days), even though the initial wind perturbation is moderately smaller. And as expected, the strengthening of 16W acts to weaken the subtropical ridge, inducing a deep-layer flow that possesses a stronger component toward the northeast than the control simulation over the first 36 h.

4) SC: LOCAL PERTURBATION

It is impossible to completely separate the sensitivity of a tropical cyclone to the perturbed evolution of synoptic-scale features from the sensitivity to the initial $V_{\text{perturbation}}$ at or near the TC. To investigate the sensitivity of Sinlaku to adjacent perturbations in the absence of changes to the synoptic environment, a new perturbation (SC) is created. SC is selected to be 200 km to the northwest of Sinlaku, directly in its path with a perturbation value of 0.59 m s$^{-1}$ at the TC that is chosen to be

Fig. 6. As in Fig. 5, but for the perturbation at S2 using $\sigma_{\text{max}} = -0.25$.

Fig. 7. As in Fig. 4, but for perturbations at (a) S3 and (b) S4.
identical to the corresponding value produced by S1 (with $a_{\text{max}} = \pm 0.75$). The perturbation SC produced virtually no change to the 120-h track of Sinlaku, suggesting that the sensitivity in the track forecast is more likely due to the evolving perturbation in the synoptic environment than the small initial perturbation near the TC.

Another result of the SC perturbation is that an initial $V$ perturbation of $\sim 1 \text{ m s}^{-1}$ at the TC resulted in a 15-km track forecast degradation at 48 h. This is of the same order as the increase in track errors seen in the other perturbations. Therefore, the initial degradations in the track forecast from the other perturbations may be due to a small deterioration of the representation of the initial wind field near the TC, while the long-term track improvements are due to an improvement of the representation of the synoptic features in the model.

5) SE: PERTURBATION BASED ON ETKF

The sensitivity of nonlinear model simulations to perturbations selected using an objective technique remains an open question. As a preliminary investigation, an additional perturbation is created in a location of sensitivity selected by one such objective technique, the ETKF. The ETKF uses ensemble Kalman filtering theory to estimate the reduction in forecast error variance due to the assimilation of any given deployment of targeted observations (Bishop et al. 2001). The version of the ETKF modified for use with tropical cyclones (Majumdar et al. 2011) is employed here. After removing the axisymmetric component of the vortex from each ensemble member, ensemble perturbations are computed about the ensemble mean. From these perturbations, estimates of the analysis and forecast error covariance matrices based on the assimilation of a simplified representation of the observational network can then be computed. In this study, the reduction in 48-h wind forecast error variance localized in a verification region centered on the TC is produced for an array of hypothetical column observations of horizontal wind, temperature, and specific humidity sampled at 200, 500, and 850 hPa at the initial time (0000 UTC 10 September 2008 for Sinlaku). A 50-member ECMWF ensemble, initialized 2 days prior to the initial time, is used in the computations. The ETKF summary map guidance is a plot of the reduction in wind forecast error variance as a function of the location of the hypothetical observations (Fig. 8a). The maximum sensitivity to potential observations is exhibited in the vicinity of Sinlaku, with secondary maxima coincident with S2, S3, and a likely spurious target far to the northeast of Sinlaku. However, there is relatively low sensitivity to observations in the base of the trough S1. Instead, an ETKF maximum exists in an area downstream of the trough axis, and this target is labeled SE. The WRF forecast sensitivity to the application of initial perturbations of strength $a_{\text{max}} = \pm 0.75$ (Fig. 8b) is found to be slightly weaker than the sensitivity to the $a_{\text{max}} = \pm 0.75$ perturbations applied to S3 and S4, with a 5-day track forecast error of 281 km, still less than half the error of the control simulation.

6) INTERCOMPARISON OF SINLAKU PERTURBATIONS

Overall, it is evident that Typhoon Sinlaku exhibits sensitivity to a variety of targets in both the near and far synoptic environments. The $\pm 0.23$ perturbation at S1, the $\pm 0.75$ perturbation at S2, and the $\pm 0.75$ perturbation at S3 all generate a maximum initial deep-layer mean wind perturbation of 4.9 m s$^{-1}$ at their targets, with small $V$ perturbations of similar magnitude at Sinlaku. (Target S4 is not considered in this comparison, since a perturbation of 4.9 m s$^{-1}$ would correspond to an unrealistically drastic modification to Tropical Storm 16W.) Given the similarity in the magnitudes of these
perturbations, one may suggest via the magnitude of the 120-h track changes (Table 1) that Sinlaku is more sensitive to the perturbation of the smaller, but significantly closer, short wave. To corroborate this argument from a different angle, the magnitude of the velocity perturbation in S1 would need to exceed 15 m s$^{-1}$ in order to generate a modification to the track comparable to S2. We therefore suggest that the track of Sinlaku is more sensitive to S2 than either S1 or S3 when the initial wind perturbations are similar.

It should be emphasized that the results are dependent on the size and strength of the perturbation, and not only the location. For example, it is evident from Table 2 that certain perturbations of S3 and S4 yield larger improvements in the track forecast than some perturbations of S1 and S2.

As mentioned above, those perturbations that resulted in an improvement in the 120-h track forecast had degraded the 48-h forecast. However, the perturbations that produced the greatest improvement in the 5-day track forecast ($-0.23$ at S1, $-0.25$ at S2, and $-0.75$ at S3 and S4) did not degrade the 48-h track forecast by more than 60 km. These short-term deteriorations are of similar magnitude to what is expected to result from the effects of the initial $V$ perturbations in the vicinity of the TC, acting to degrade the initial motion of the TC, while long-term track improvements are associated with either an improvement in the initial representation of the synoptic environment of Sinlaku or a compensation for errors produced by the perturbations.


a. Synopsis and selection of targets

Hurricane Ike was entering the Gulf of Mexico on 0000 UTC 9 September 2008, the initial time of interest for this study. At that time, Ike was situated along the southern coast of Cuba, possessing maximum sustained winds of 70 kt (averaged over 1 min), and traveling toward the west-northwest on the southern periphery of a strong anticyclone (Fig. 9a). The deep-layer mean flow was considerably stronger than that of Sinlaku, given that Ike was propagating at 11 kt at the time. Ike continued in a general west-northwestward direction until 1200 UTC 13 September, before undergoing recurvature due to interaction with a short-wave trough over the southwestern United States.

The forecasts initialized on 0000 UTC 9 September 2008 were noteworthy since the consensus of model forecasts available to the National Hurricane Center for landfall shifted erroneously southward toward the Texas–Mexico border, following earlier forecasts that had depicted a landfall along the north Texas coast (Brennan and Majumdar 2011). The WRF control simulation exhibits a similar erroneous track (Fig. 9b) as several operational models initialized at that time. The control is accurate over the first day, after which the error grows steadily and linearly by approximately 100 km day$^{-1}$ over the following 3 days. This error growth is associated with a deviation that tracks progressively farther south relative to the best track. During days 4 and 5, the control forecast of Ike remains to the south and avoids interaction with the approaching short wave, thereby incorrectly avoiding recurvature. The forecast error grows rapidly from 317 to 859 km between days 4 and 5.

For several features including the ridge to the north of Ike, the differences between the 84-h control simulation and the corresponding ECMWF analysis used for verification are relatively minor. However, the control exhibits a less amplified long-wave pattern over the continental United States than does the analysis (Figs. 10a and 10b). In the analysis, a short wave embedded...
within the long-wave trough over the western United States merges with neighboring short waves along the southern end of the long wave and propagates as far south as the latitude of Ike, ultimately contributing to the recurvature of Ike (Fig. 10a). On the other hand, the simulated short waves approaching the western United States at this time are too positively tilted at 500 hPa and have not moved as far south (Fig. 10b). The vertical cross section in the analysis reveals a strong (25–30 m s⁻¹) and broad southwesterly jet with two maxima, one at 300 hPa and one above 200 hPa (Fig. 10c). In contrast, the control simulation exhibits a narrower and shallower southwesterly jet with only one maximum at and above 200 hPa, and which is farther from Ike than that in the analysis (Fig. 10d). The discrepancy between the long-wave patterns in the control and the verifying analysis suggests that Ike is less likely to undergo a strong recurvature in the control simulation.

Several features within the environment of Ike are designated as targets for perturbation, including the subtropical ridge, three upper-level short-wave troughs, and two low-level short-wave troughs that are potential candidates to modify the propagation and subsequent recurvature of Ike (Fig. 11). Values of $a_{\text{max}}$ and the perturbation radii for each target are given in Table 3. The first target is the western periphery of the 500–850-hPa subtropical anticyclone immediately to the north of Ike (designated IR). Although the ridge is a broad feature, a perturbation radius of 400 km is selected to prevent modification to the initial structure of Ike. The three upper-level troughs in which perturbations are made between 200 and 500 hPa compose a strong short wave to the west of the Great Lakes (I1), a much weaker upper-level low east of the Bahamas (I2), and a short wave of moderate intensity along the west coast of California (I5). I1 is deemed a potentially significant per-turbation target.
target due to its size and strength, and therefore its potential ability to modify the long-wave pattern in the midlatitudes. Target I2 is selected due to its proximity to Ike. Target I5, which is embedded within a long-wave trough, merges with other short waves to produce the short wave that is illustrated 84 h later in Fig. 10, and which is responsible for the recurvature of Ike. The three lower-level short waves in which perturbations are made between 500 and 850 hPa compose a small short wave at the tail end of a cold front over Texas and Oklahoma (I3), Tropical Storm Lowell south of Baja California (I4), and the low-level reflection of target I5. Note that target region I5 is perturbed at both upper and lower levels, due to the existence of both upper- and lower-level short waves within the same region. Target I3 bypasses Ike by less than 2000 km to the north. I4 is of interest given that Lowell is advected toward the northeast within the subtropical jet and may interact with the short waves that influence the recurvature of Ike. Perturbations in a midlatitude target identified by the ETKF (IE) and in a region local to Ike (IC) are also investigated (Fig. 11). The ETKF targets the leading edge of the midlatitude trough for both Sinlaku and Ike (SE and IE).

b. Sensitivity to perturbations

The sensitivity study of Ike utilizes a uniform $\alpha_{\text{max}} = \pm 0.75$ perturbation to all targets, except IC, consistent with the Sinlaku study. Similar to S2, $\alpha_{\text{max}}$ for IR is incrementally reduced to zero to demonstrate that, for some less-extreme modification of the ridge, there exists a set of initial conditions that will accurately depict the best track for Ike. A comparison at I1 between simulations in which $\alpha_{\text{max}} = \pm 0.75$ and $\pm 1.00$ demonstrates the

![Figure 11](image_url)

**FIG. 11.** ECMWF analysis within WRF domain valid at 0000 UTC 9 Sep 2008. (a) The 500–200-hPa layer mean relative vorticity (shaded) and deep-layer mean vector wind (arrows) with upper-level targets I1 and I2 and (b) the 850–700-hPa layer mean relative vorticity with low-level targets IR, I3, I4, and I5. The vorticity maximum adjacent to Cuba is Hurricane Ike.

<table>
<thead>
<tr>
<th>Target</th>
<th>$\alpha_{\text{max}}$</th>
<th>$r_{\text{pert}}$ (km)</th>
<th>Distance (km)</th>
<th>ETKF</th>
<th>$V_{\text{max}}$ at target (m s$^{-1}$)</th>
<th>$V_{\text{max}}$ at TC (m s$^{-1}$)</th>
<th>48-h $\Delta$track (km)</th>
<th>120-h $\Delta$track (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IR</td>
<td>-0.75</td>
<td>400</td>
<td>1100</td>
<td>0.54</td>
<td>4.1</td>
<td>1.1</td>
<td>280</td>
<td>1042</td>
</tr>
<tr>
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<td>-0.55</td>
<td>400</td>
<td>1100</td>
<td>0.54</td>
<td>3.0</td>
<td>0.8</td>
<td>186</td>
<td>756</td>
</tr>
<tr>
<td>IR</td>
<td>-0.35</td>
<td>400</td>
<td>1100</td>
<td>0.54</td>
<td>1.9</td>
<td>0.5</td>
<td>112</td>
<td>524</td>
</tr>
<tr>
<td>I1</td>
<td>+1.00</td>
<td>600</td>
<td>2700</td>
<td>0.70</td>
<td>15.5</td>
<td>1.4</td>
<td>350</td>
<td>709</td>
</tr>
<tr>
<td>I1</td>
<td>+0.75</td>
<td>600</td>
<td>2700</td>
<td>0.70</td>
<td>11.6</td>
<td>1.1</td>
<td>284</td>
<td>600</td>
</tr>
<tr>
<td>I1</td>
<td>+0.22</td>
<td>500</td>
<td>2700</td>
<td>0.70</td>
<td>3.3</td>
<td>0.3</td>
<td>66</td>
<td>180</td>
</tr>
<tr>
<td>I2</td>
<td>-0.75</td>
<td>500</td>
<td>1500</td>
<td>0.65</td>
<td>3.3</td>
<td>0.3</td>
<td>20</td>
<td>132</td>
</tr>
<tr>
<td>I3</td>
<td>+0.75</td>
<td>400</td>
<td>2400</td>
<td>0.75</td>
<td>2.0</td>
<td>0.1</td>
<td>20</td>
<td>46</td>
</tr>
<tr>
<td>I4</td>
<td>-0.75</td>
<td>400</td>
<td>3400</td>
<td>0.78</td>
<td>5.4</td>
<td>0.2</td>
<td>0</td>
<td>327</td>
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<tr>
<td>I5</td>
<td>+0.75</td>
<td>500</td>
<td>4500</td>
<td>N/A</td>
<td>3.5</td>
<td>0.1</td>
<td>20</td>
<td>66</td>
</tr>
<tr>
<td>IC</td>
<td>+0.04</td>
<td>400</td>
<td>200</td>
<td>0.80</td>
<td>1.2</td>
<td>1.1</td>
<td>0</td>
<td>46</td>
</tr>
<tr>
<td>IE</td>
<td>+0.75</td>
<td>600</td>
<td>2600</td>
<td>0.91</td>
<td>10.7</td>
<td>0.7</td>
<td>198</td>
<td>544</td>
</tr>
</tbody>
</table>
difference between substantially weakening (strengthening) a short wave and removing (doubling) the short wave altogether. A perturbation of ±0.22 is applied to I1 in order to produce a \(|V|_{\text{max}} = 6\) perturbation at I1, equal to \(|V|_{\text{max}} = 15.5\) for comparison. Finally, a ±0.04 perturbation is applied to IC in order to produce a \(V^2\) perturbation of average magnitude equal to 1 m s\(^{-1}\) within a 300-km radius of Ike.

1) IR: ATLANTIC RIDGE

Target IR is perturbed using \(\alpha_{\text{max}} = ±0.75, ±0.55,\) and ±0.35, generating maximum 850–200-hPa wind perturbations of 15.5, 11.6, and 3.3 m s\(^{-1}\), respectively, at the target (Table 3). The WRF simulation initialized with \(\alpha_{\text{max}} = -0.35\), which corresponds to a modest weakening of the initial ridge, produces a track that resembles the best track for the first 3 days (Fig. 12a). While recurvature occurs at the correct time in this simulation, the forward velocity of Ike is too slow, producing recurvature too far south and 5-day forecast errors of approximately 400 km, mostly along track. However, this track error is less than half of that of the control. A summary of the track errors in the control and various perturbed simulations is given in Table 4.

The initial weakening of the subtropical ridge produces a negative meridional wind (\(\nu\)) perturbation to the north-northwest of Ike and a positive \(v\) perturbation to the north-northeast of Ike (Fig. 13a). Within the first 24 h, the negative \(\nu\) perturbation diminishes, while the positive \(v\) perturbation grows (Figs. 13b and 13c). The positive perturbation, corresponding to a strengthening of the southerly wind component, amplifies thereafter, allowing Ike to propagate 100 km farther north in the perturbed simulation than the control at 48 h (Fig. 13d). The far-field propagation of the perturbation signal beyond 48 h is evident off the Eastern Seaboard, and eventually within the long-wave pattern (Figs. 13d–f).

While the perturbed simulation of Ike remains less than 200 km north of the control simulation through to 72 h (Fig. 13e), this gain in latitude and slow motion is sufficient for Ike to fall under the influence of the approaching trough over the southwestern United States, resulting in recurvature at 108 h (Fig. 13f). Also note that the weakening of the IR ridge has allowed the western United States trough to extend farther south by 108 h, inducing strengthened southerlies over the southern United States and western Gulf of Mexico. The recurvature in the perturbed simulation is proposed to be primarily a consequence of the gain in latitude of Ike, which is attributed to the weakening of the western periphery of the Atlantic ridge. The southward shift of the long-wave trough also likely contributes to the recurvature.

2) I1: MIDLATITUDE TROUGH

Target I1 is perturbed using \(\alpha_{\text{max}} = ±0.22, ±0.75,\) and ±1.00, generating maximum 850–200-hPa wind

### Table 4. As in Table 2, but for Hurricane Ike initialized on 0000 UTC 9 Sep 2008.

<table>
<thead>
<tr>
<th>Target</th>
<th>(\alpha_{\text{max}})</th>
<th>48 h</th>
<th>60 h</th>
<th>72 h</th>
<th>84 h</th>
<th>96 h</th>
<th>108 h</th>
<th>120 h</th>
</tr>
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<tbody>
<tr>
<td>CTRL</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IR</td>
<td>-0.75</td>
<td>+49</td>
<td>+64</td>
<td>+121</td>
<td>+161</td>
<td>+131</td>
<td>-66</td>
<td>-169</td>
</tr>
<tr>
<td>IR</td>
<td>-0.55</td>
<td>-41</td>
<td>-54</td>
<td>-40</td>
<td>-30</td>
<td>-79</td>
<td>-273</td>
<td>-520</td>
</tr>
<tr>
<td>IR</td>
<td>-0.35</td>
<td>-98</td>
<td>-149</td>
<td>-149</td>
<td>-144</td>
<td>-148</td>
<td>-298</td>
<td>-452</td>
</tr>
<tr>
<td>I1</td>
<td>+1.00</td>
<td>+113</td>
<td>+153</td>
<td>+232</td>
<td>+225</td>
<td>+109</td>
<td>-80</td>
<td>-331</td>
</tr>
<tr>
<td>I1</td>
<td>+0.75</td>
<td>+47</td>
<td>+49</td>
<td>+90</td>
<td>+74</td>
<td>-4</td>
<td>-181</td>
<td>-386</td>
</tr>
<tr>
<td>I1</td>
<td>+0.55</td>
<td>-65</td>
<td>-74</td>
<td>-51</td>
<td>-62</td>
<td>-52</td>
<td>-112</td>
<td>-180</td>
</tr>
<tr>
<td>I1</td>
<td>+0.35</td>
<td>-20</td>
<td>-23</td>
<td>-10</td>
<td>-29</td>
<td>-30</td>
<td>-92</td>
<td>-127</td>
</tr>
<tr>
<td>I2</td>
<td>+0.75</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td>25</td>
<td></td>
</tr>
<tr>
<td>I2</td>
<td>+0.55</td>
<td>0</td>
<td>-39</td>
<td>-18</td>
<td>-62</td>
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<td>-198</td>
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</tr>
<tr>
<td>I2</td>
<td>+0.35</td>
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<td>0</td>
<td>-3</td>
<td>31</td>
<td>29</td>
<td>43</td>
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</tr>
<tr>
<td>IC</td>
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<td>0</td>
<td>0</td>
<td>+18</td>
<td>-17</td>
<td>-30</td>
<td>-62</td>
<td>-46</td>
</tr>
<tr>
<td>IC</td>
<td>+0.22</td>
<td>0</td>
<td>0</td>
<td>+18</td>
<td>-17</td>
<td>-30</td>
<td>-62</td>
<td>-46</td>
</tr>
<tr>
<td>IC</td>
<td>+0.75</td>
<td>-38</td>
<td>-34</td>
<td>-11</td>
<td>-20</td>
<td>-45</td>
<td>-177</td>
<td>-392</td>
</tr>
<tr>
<td>IC</td>
<td>+0.75</td>
<td>-38</td>
<td>-34</td>
<td>-11</td>
<td>-20</td>
<td>-45</td>
<td>-177</td>
<td>-392</td>
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<td>IE</td>
<td>+0.75</td>
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<td>-20</td>
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<td>-392</td>
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</table>
perturbations of 3.3, 11.6, and 15.5 m s\(^{-1}\), respectively, at the target. Weakening the short wave consistently degrades the track forecast, producing a landfall south of the control (Fig. 12b). Conversely, strengthening the short wave produces landfall locations farther north of the control. A strong perturbation, \(a_{\text{max}} = 0.75\), is necessary to produce a simulated track close to the best track at longer time ranges, with an improvement over the control of nearly 400 km at 15 days. However, in improving the long-range track forecast and landfall location, the short-range track forecast is slightly deteriorated due to a northward bias.

The initial perturbation yields a stronger southerly (northerly) wind component on the eastern (western) side of the short wave (Fig. 14a). During the first 12 h, the control and perturbed tracks remain similar (Fig. 12), given the time necessary for the initially remote perturbation to reach the immediate environment of Ike (Fig. 14b). By 24 h, a southward extension of positive perturbations of meridional wind dominates the environment of Ike, increasing the southerly component of the deep-layer flow and producing a simulated track northward of the best track (Fig. 14c). By 48 h, the evolved perturbations are generally neutral around Ike, leading to a track parallel to the control simulation, albeit with slightly higher track errors (Fig. 14d). Concurrent with the direct initial change to Ike’s track, the midlatitude long- and short-wave patterns are also modified via the I1 perturbation. This modification begins when the short wave associated with I1 lifts to the northeast, leading to a ridge building in from the west. This ridge is more amplified in the perturbed simulation than in the control, consistent with the differences between the verifying analysis and the control. Farther upstream, the short wave initially over the Pacific Northwest is propagating southward, more so in the perturbed simulation. By 72 h, a phase difference is evident in the short wave around 42°N, 110°W, with positive vorticity perturbations to the west of and extending farther south than the negative perturbations (Fig. 14e). At the same time, the vorticity associated with the local maximum over Southern California is shifted to the east. This suggests that the pattern is less positively tilted than in the control forecast, resulting in landfall over northern Texas at 108 h (Fig. 14f). In summary, the strengthening of vorticity at I1 amplifies the synoptic pattern in two ways: a direct increase in the southerly component of winds near Ike, followed by interaction with a short-wave trough modified by the upstream influence of the I1 perturbation. The upstream and downstream propagations of

**Fig. 13.** (a)–(c) Colors show the meridional wind difference (m s\(^{-1}\)) between the perturbed \((a_{\text{max}} = 0.35)\) and control WRF simulations for (a) 0, (b) 12, and (c) 24 h. Vectors show the 850–200-hPa layer mean wind in the perturbed simulation. (d)–(f) Contours show the 500–200-hPa layer mean relative vorticity \(2 \times 10^{-5} \text{ s}^{-1}\); positive, dashed; negative, dotted). Colors show the relative vorticity difference between the perturbed and control simulations \(3 \times 10^{-4} \text{ s}^{-1}\) at (d) 48, (e) 72, and (f) 108 h. The location of Ike at the corresponding time is indicated by the TC symbol.
the short-wave perturbations in the midlatitude storm track have been observed in both the I1 and S1 perturbations, consistent with the results of Simmons and Hoskins (1979), who had determined that upstream and downstream development occurs in nonlinear simulations of an initially local perturbation in zonal baroclinic flows.

3) **I4: TROPICAL STORM LOWELL**

The perturbation I4 ($\alpha_{max} = -0.75$), corresponding to the weakening of Tropical Storm Lowell, produces virtually no change to the track forecast up to 84 h, followed by a modest recurvature and improvement to the landfall location by 324 km (Fig. 15a). The weakening of Lowell produces a meridional phase shift in the relative vorticity over the U.S.–Mexico border after 1 day, and the positive part of this vorticity perturbation then spreads northward and splits. The western branch of this positive perturbation maintains its position over the southwestern United States, increasing slightly in magnitude to produce a coherent signature in the evolved vorticity perturbation by 84 h (Fig. 15b). The double dipole over the western United States corresponds to the large-scale pattern becoming less positively tilted, improving the consistency with the verifying analysis in Fig. 10a. Unlike the IR and I1 cases, there is negligible modification to the flow adjacent to Ike prior to its interaction with the short wave. It is therefore suggested that the amplification of the upstream pattern due to the weakening of Lowell leads to a more accurate track forecast of Ike.

4) **OTHER PERTURBATIONS**

The WRF simulations of Ike exhibit little to no sensitivity to perturbations I2, I3, or I5, since the tracks produced by the associated perturbed simulations are almost identical to the control (not shown). For I2, a dynamical connection between the weak upper-level trough over the Atlantic and the environment of Ike is weak. For I3 and I5, the perturbations grow but only act to produce small-scale phase shifts within the subtropical jet. As had been investigated in the Sinlaku case, a perturbation (IC) is created adjacent to Ike, to produce an initial maximum velocity perturbation over Ike of $1.08 \text{ m s}^{-1}$, identical to that produced over Ike by the strong amplification of the short-wave I1 near the Great Lakes. The evolved perturbation from IC dissipates within the first 24 h, resulting in no change to the track forecast of Ike. As with Sinlaku, it is suggested that the modification to the track arises from remote sources, and not the small initial perturbation local to the tropical cyclone.

5) **IE: PERTURBATION BASED ON ETKF**

The ETKF guidance for Ike exhibits several areas of potential sensitivity to the assimilation of observations, including I3 and I4 (Fig. 16a). However, as for Sinlaku, the target in the midlatitude storm track is situated slightly

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**FIG. 14.** As in Fig. 13, but for perturbation at I1 with $\alpha_{max} = +0.75$. 

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downstream from the trough axis (labeled IE), in an area of lower vorticity but higher velocity. Also common with the Sinlaku case is the fact that a modification to the track simulation is evident when a perturbation of strength $a_{\text{max}} = 0.75$ is applied in this area (IE; see Fig. 16b). Although the reasoning for the improved track is similar to that offered for I1, the forecast errors are consistently lower than those for I1 at all times.

6) INTERCOMPARISON OF IKE’S PERTURBATIONS

Overall, in contrast to the sensitivity analysis for Sinlaku, only a limited number of perturbations were found to improve the track forecast of Ike. First, a modest weakening of the ridge directly north of Ike (IR) produced the most significant and immediate improvement. The gain in latitude due to the weakening ridge was sufficient for Ike to interact with a relatively unperturbed short-wave trough and undergo recurvature. Second, a very strong perturbation to a mid-latitude short wave (I1, IE) resulted in an improvement to the track forecast, due to a similar gain in latitude at early times, but also the amplification of the large-scale pattern upstream that assisted the recurvature. Third, a weakening of Tropical Storm Lowell (I4) did not produce a gain in latitude at early times, but served to amplify the upstream large-scale pattern resulting in a modest recurvature that the control failed to produce.

In the control and perturbed simulations, the track errors grew fastest between 4 and 5 days, at the time that Ike underwent recurvature.

In contrast with Sinlaku, the majority of the Ike perturbations that produced 120-h track improvements also improved the 48-h track forecast. This indicates that, in addition to a genuine improvement of the initial
representation of the synoptic environment in the model, the initial V perturbation at the TC produced by generating the perturbations for Ike compensated for an initial analysis error close to the TC.

5. Conclusions

An examination of the sensitivity of numerical simulations of tropical cyclone (TC) track to initial perturbations has been conducted for Typhoon Sinlaku (2008) and Hurricane Ike (2008). Balanced perturbations of different amplitude, spatial scale, and location were created via a modification of local relative vorticity at a chosen location and depth. For each TC, 5-day Advanced Research WRF simulations of 21-km resolution were integrated from the unperturbed (“control”) and perturbed initial conditions. The control simulations replicated forecast errors evident in the operational models, with a premature recurvature in the forecast for Sinlaku and a landfall too far south along the Texas coast for Ike.

It was found that several perturbed simulations of Sinlaku exhibited large modifications to its track. The greatest improvement to the track forecast occurred when the vorticity associated with either of two short waves to the north of Sinlaku was weakened, suggesting that one or both of the short waves may have been initialized too strongly, thereby contributing to an erroneous recurvature. In each case, the weakening of the short wave acted to decrease the northerly component of the flow in the deep-layer anticyclones to the west and east of Sinlaku, thereby keeping the simulated TC sufficiently far south to avoid recurvature. Perturbations to a decaying tropical storm and the monsoon trough to the southwest also yielded modifications to the track, demonstrating that this forecast case was likely one of unusually low predictability. While all perturbations resulted in increased short-term track errors, those simulations that produced the greatest improvement in long-term track performance only degraded the 48-h track forecast by 85 km or less. These simulations correspondingly improved the 120-h track forecast by 363 km or more.

In contrast to the Sinlaku case, the strengthening or weakening of vorticity in the synoptic environment of Ike exhibited weaker sensitivity for several choices of perturbation. The highest sensitivity was found when the adjacent Atlantic ridge north of Ike was weakened slightly, thereby increasing the southerly component of the deep-layer mean wind and producing a gain in latitude that was sufficient for the perturbed simulation of Ike to undergo recurvature around the time of landfall in northern Texas. This gain in latitude was not produced in many simulations, including the control. A second feature of sensitivity was a short-wave trough in the midlatitude jet, although a strong perturbation that amplified the upper-level relative vorticity by 75% was necessary for this simulation to be consistent with the best track. The modifications to Ike’s track in this case were due to a strengthening of the southerly component of the flow near Ike, and an amplification of the large-scale midlatitude pattern via upstream propagation of the perturbation, which acted to reduce the positive tilt of a short-wave trough over the western United States. The weakening of Tropical Storm Lowell in the eastern North Pacific basin induced a modest recurvature, due to a similar modification of the pattern over the western United States.

The ETKF indicated several similar target regions to those selected subjectively, for both cases. However, its ranking of the targets, based on reduction of wind forecast error variance in the tropical cyclone, was inconsistent with those concluded from the perturbation experiments. In particular, the ETKF did not identify the ridge immediately due north of Ike as an important target for supplementary observations, due in part to the low variance in the ensemble perturbations in that region. Consistency between the ETKF targets and locations of maximum initial condition sensitivity found in this paper is not necessarily expected, given that the ETKF is an observation sensitivity method that assumes ensemble-based data assimilation and is correct only when error covariance information is perfect and the model dynamics are linear.

The methodology offered in this paper offers a retrospective qualitative understanding of environmental features that may or may not be important in governing the track forecast of a TC, for a particular model. It should be noted that the results are dependent upon the user’s choice of the strength and spatial extent of the initial perturbation. The perturbations are confined to local features (such as individual short waves), and therefore the technique is applicable to resolving questions about where local corrections to the analysis may have led to improved forecasts, either via selective regional targeting of observations or improvements to the data assimilation. Finally, the technique may be utilized to evaluate the efficacy of objective initial condition sensitivity methods and related initialization methods for ensemble forecasts.

Acknowledgments. The authors acknowledge funding from the Office of Naval Research (Grant N00014-08-1-0251). The authors are also grateful to Chris Velden, Rolf Langland, and David Nolan for their comments.
and advice throughout the study. Detailed suggestions by two anonymous reviewers helped improve the paper.

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