Predictability and genesis of Hurricane Karl (2010) examined through the EnKF assimilation of field observations collected during PREDICT

JONATHAN POTERJOY AND FUQING ZHANG*

Department of Meteorology, The Pennsylvania State University, University Park, Pennsylvania

*Corresponding author address: Professor Fuqing Zhang, Department of Meteorology, the Pennsylvania State University, University Park, PA 16802.

E-mail: fzhang@psu.edu
ABSTRACT

The genesis of Hurricane Karl (2010) is explored using analyses and forecasts from a cycling ensemble Kalman filter (EnKF) that assimilates routinely collected observations as well as dropsonde measurements that were taken during the Pre-Depression Investigation of Cloud Systems in the Tropics (PREDICT) field campaign. A total of 127 dropsonde observations were collected from six PREDICT flight missions, over a five-day period before and during Karl’s genesis. EnKF analyses that take into account the PREDICT dropsondes provide a detailed four-dimensional overview of the evolving kinematic and thermodynamic structure within the pre-genesis disturbance. In particular, the additional field observations are found to increase the low- and mid-level circulation and column moisture in the EnKF analyses, and reduce the position error of the low-level vortex. Deterministic forecasts from these analyses show a 24-h improvement in predicting genesis over a control experiment that omits the dropsonde observations. In ensemble forecasts for this event, the more accurate analyses translate into a higher confidence in predicting the intensification of Karl; i.e., a larger number of ensemble members capture the correct timing of genesis and rapid intensification. The cycling data assimilation experiments also suggest that initial condition errors at the mesoscale pose large challenges for predicting genesis, thus highlighting the need for improved observation networks and more advanced data assimilation methods.
1. Introduction

The formation of a tropical cyclone is typically preceded by the development of a synoptic-scale disturbance; e.g., a low-pressure system along a tropical wave, a monsoon trough or an extratropical cyclone. For the case of tropical waves, observational and modeling studies support a range of explanations as to how a tropical weather system can generate a self-sustained cyclone. Among these studies, some propose a “top-down” process in which stratiform precipitation associated with mesoscale convective systems within the synoptic-scale disturbance acts to moisten and cool the column of air between the lower and middle troposphere, which leads to a gradual lowering of the mid-level cyclone (Bister and Emanuel 1997; Ritchie and Holland 1997; Simpson et al. 1997). An alternative theory suggests that genesis follows a “bottom-up” process, in which the low-level cyclonic circulation intensifies via the merging of convectively-induced vorticity anomalies (Hendricks et al. 2004; Reasor et al. 2005; Montgomery et al. 2006; Halverson et al. 2007). More recent studies emphasize a multi-scale pathway to genesis. Dunkerton et al. (2009) hypothesize that genesis is favored within a region of approximately closed Lagrangian circulation in the synoptic-scale disturbance, where cloud-scale vorticity anomalies are protected from the entrainment of relatively dry environmental air. Vorticity and column moisture are allowed to build up in this region until the eventual formation of a tropical cyclone. Fang and Zhang (2010, 2011) show that accumulative heating from convective cells within the vortex can amplify the quasi-balanced system-scale circulation, which in turn produces a secondary circulation that organizes the cloud-scale vorticity anomalies.

Regardless of the path to genesis, the process by which a tropical cyclone forms and
intensifies is sensitive to the synoptic- and meso-scale wind and moisture features in the
pre-genesis disturbance. In ensemble simulations of developing and non-developing tropical
cyclones, Sippel and Zhang (2008, 2010) found genesis and intensification to be highly sensi-
tive to the amount of deep moisture and convective available potential energy (CAPE) in the
initial conditions. Zhang and Tao (2013) showed that vertical wind shear further decreases
the predictability of intensity by amplifying the effects of small-scale errors in the moisture
field. They found that differences in moist convection could alter the tilt amplitude and angle
of the incipient tropical storm vortex, which can lead to significant differences in the onset
of genesis and rapid intensification. Using empirical orthogonal functions (EOFs), Torn and
Cook (2013) found ensemble forecasts for the genesis of Hurricanes Danielle and Karl (2010)
to be most sensitive to the low-level circulation and the mid- to upper-level thermodynamic
fields of the pre-genesis system, with a smaller sensitivity to the environmental conditions.
From these studies, it follows that the skill of a numerical model in predicting genesis must
depend on the availability of observations and the effectiveness of a data assimilation system
in generating accurate initial conditions.

The Pre-Depression Investigation of Cloud Systems in the Tropics (PREDICT) field
campaign was carried out during the 2010 Atlantic hurricane season to collect detailed drop-
sonde observations in the vicinity of tropical waves prior to the development of a tropical
depression (Montgomery et al. 2012). With the ultimate goal of finding new precursors
for genesis, the targeted tropical waves include weather systems that formed and did not
form tropical cyclones. One objective of the PREDICT experiment is to examine the pre-
ddictability of tropical cyclogenesis with state-of-the-art ensemble analysis and forecasting
systems. Two experimental ensemble Kalman filter (EnKF) data assimilation systems based
on the Weather Research and Forecast (WRF) model were used during PREDICT to pro-
vide short-range (24-72 h) guidance for mission planning. Examples of real-time ensemble
forecasts from these two systems are presented in Montgomery et al. (2012). Given the
initial condition and modeling uncertainty associated with tropical cyclogenesis forecasts,
this aspect of the experiment requires high-resolution in-situ observations to further explore
both the practical and intrinsic predictability of genesis.

To investigate the potential benefits of assimilating field observations near a pre-genesis
tropical disturbance, the current study uses an ensemble data assimilation system that was
used in real time for PREDICT (i.e., The Pennsylvania State University WRF-EnKF).
All conventional non-radiance data along with dropsondes collected during PREDICT flight
missions are assimilated over a 10-day period in which a tropical disturbance transitioned into
Hurricane Karl (2010). Analyses from three sets of cycling data assimilation experiments are
compared to explore the synoptic- and meso-scale evolution of the tropical weather system
prior to genesis. The first two experiments use a 13.5-km domain to examine the utility of
PREDICT observations in producing accurate analyses of Karl, while the third experiment
uses a 4.5-km domain to test the sensitivity of the data assimilation to model resolution.
Both deterministic and ensemble forecasts are used to assess changes in predictability for
Karl at different lead times during the cycling.

The organization of the manuscript is as follows. Section 2 provides a synopsis of Hurri-
cane Karl and presents the timeline for the PREDICT flight missions leading up to genesis.
It also describes the model and data assimilation systems used during this study, as well
as the design of the cycling data assimilation experiments. Section 3 contains an overview
of the analysis results from the set of data assimilation experiments, while sections 4 and
5 present deterministic and ensemble forecast results, respectively. Section 6 compares results from the 13.5- and 4.5-km data assimilation experiments and section 7 summarizes the conclusions of this study.

2. Experiment setup

a. Overview of Hurricane Karl and the PREDICT dropsondes

Karl was a major hurricane from the 2010 Atlantic season that formed in the northwestern Caribbean Sea and made landfall twice on the coast of Mexico. It developed from a broad westward propagating cyclone that initiated near the northern coast of South America on 8 September. The National Hurricane Center (NHC) began forecasting a medium to high 48-h probability of genesis as early as 9 September, but the actual depression did not form until 12 UTC 14 September (Stewart 2010). Owing to its slow development, the pre-Karl disturbance was the most observed event during the PREDICT field campaign. In the five days leading up to genesis six flight missions were carried out using the National Science Foundation (NSF)-National Center for Atmospheric Research (NCAR) Gulfstream V (GV) aircraft (Montgomery et al. 2012). Shortly after becoming a named tropical storm, Karl passed over the Yucatan Peninsula and rapidly intensifying into a strong category three hurricane on the Saffir-Simpson scale. Predicting the intensity of Karl remained a great challenge for forecasters, even after it became a self-sustained tropical cyclone. Karl's rapid intensification over the Bay of Campeche was not represented well in operational forecast models, which led to official intensity forecast errors that were well above average (Stewart
Figure 1 summarizes the track and intensity changes of the weather system, starting from the pre-Karl disturbance on 9 September and ending with its decay over Mexico on 18 September. Intensity and track observations of the tropical cyclone are taken from the NHC best-track dataset, while the pre-genesis storm positions come from the wave tracking product described in Wang et al. (2012). The figure also indicates the positions of PREDICT dropsonde observations that were collected during each flight mission. These dropsondes were launched at altitudes between 150- and 200-mb, and span a region that covers the inner 7.5 degrees (~800 km) of the storm center.

b. WRF model

The Advanced Research WRF version 3.4.1 (Skamarock et al. 2008) is used for this study with an outer domain that covers the Gulf of Mexico and Caribbean Sea with a 251 x 226 horizontal grid at a spacing of 13.5 km (black box in Fig. 1). A two-way nested inner domain follows the disturbance using a 253 x 253 horizontal grid at a spacing of 4.5 km. Each domain has 35 vertical levels, most of which are concentrated in the lower troposphere, and a model top of 5 mb. The physical parameterization schemes include WRF single-moment 6-class microphysics (Hong et al. 2004), the Rapid Radiative Transfer Model (RRTM, Mlawer et al. 1997) and Dudhia (Dudhia 1989) radiation schemes, Monin-Obukhov similarity (Monin and Obukhov 1954) for the surface layer, 5-layer thermal diffusion for surface layer physics, and the Yonsei University planetary boundary layer scheme (Noh et al. 2003). Sensitivity experiments with and without the parameterization of cumulus physics show improved results when convection was represented explicitly in both domains,
so cumulus parameterization is turned off for this case study.

c. WRF-EnKF data assimilation

This study uses the WRF-EnKF data assimilation system developed originally by Meng and Zhang (2008a,b), and adapted later for tropical cyclones in Zhang et al. (2009, 2011) and Weng and Zhang (2012). Since 2008, this system has been used in real time to assimilate routinely-collected radial velocity observations from NOAA P3 airborne Doppler radar flight missions and provide forecasts for tropical cyclones in the Atlantic hurricane basin. The EnKF uses an ensemble forecast to advance a flow-dependent background error covariance matrix between data assimilation cycles, thus acting as an approximation to the extended Kalman filter (Evensen 1994). Ensemble perturbations are updated around the posterior mean state using the square-root algorithm described in Whitaker and Hamill (2002). To treat sampling errors, the ensemble-estimated background covariance is localized using an element-wise multiplication of the covariance matrix with a Gaspari and Cohn (1999) fifth-order correlation function, and perturbations are inflated after each analysis using the “covariance relaxation to the prior” method proposed in Zhang et al. (2004). For this study the EnKF uses 60 members with a horizontal localization radius of 900 km, a vertical localization radius of 15 vertical levels and a relaxation coefficient of 0.8; i.e., 80% of the updated perturbation is relaxed back to the prior. See Poterjoy and Zhang (2013) for a discussion on sampling errors pertaining to this data assimilation system.
d. **Experiment design**

Perturbations are sampled from a climatological background error covariance matrix\(^2\) and added to the Global Data Assimilation System (GDAS) analysis at 18 UTC 7 September to generate the initial ensemble of model states. The ensemble members are then integrated forward for twelve hours before assimilating the first set of observations on 06 UTC 8 September. This integration period enables the ensemble to develop physically consistent flow-dependent covariance structures before the first cycle. The GDAS data are also used throughout the experiments to provide lateral boundary conditions for the limited-area model, and to provide sea surface temperatures that remain fixed throughout each simulation.

Following the first ensemble forecast, the EnKF assimilates all non-radiance observations from the NOAA Meteorological Assimilation Data Ingest System (MADIS) every six hours between 06 UTC 8 to 00 UTC 18 September. These observations include surface data, routine soundings, and cloud-tracked winds from Geostationary Operational Environmental Satellites (GOES). Observations that are collected within three hours of the analysis time are assimilated at a given cycle using the same time stamp as the analysis. The beginning of the cycling period corresponds to the first identification of the pre-Karl disturbance by the NHC, and the last cycle occurs as Karl decays over the Mexican coast. This data assimilation experiment (denoted “EnKF-MADIS”) provides the control in our study, since field observations are not used in the analyses. In a second experiment (denoted “EnKF-PREDICT”) the data assimilation is repeated from 12 UTC 10 September to the end of the

\(^2\)The background error is estimated from 24- and 12-h forecast differences over the previous month using the National Meteorological Center (NMC) method (Parrish and Derber 1992). The calculation is performed using the gen_be utility in the WRF data assimilation package with control variable option 5.
cycling period to generate a set of analyses that takes into account both the MADIS and the PREDICT observations. Both of these experiments use the 13.5-km domain to perform the ensemble forecast and data assimilation stages of the cycling and apply the nested 4.5-km domain when generating deterministic forecasts only. We then perform a third experiment (denoted “EnKF-4.5km”) using the 4.5-km grid spacing nest during all stages of the cycling to examine the impact of increasing the resolution of the near-disturbance analyses. This experiment uses the same observations as the EnKF-PREDICT case and will be discussed separately from the two experiments that use a single 13.5-km grid spacing domain during data assimilation.

3. Analysis results

a. Vortex evolution

This section compares the EnKF mean analyses for the MADIS and PREDICT experiments between 12 UTC 10 and 00 UTC 18 September, a period that begins at the first flight mission time and ends on the last data assimilation cycle. In addition to providing initial conditions for deterministic and ensemble forecasts, these analyses are used as a dataset for studying the time evolution of the pre-genesis disturbance. We use the region within three degrees of the circulation center in the analyses to examine the kinematic structure of the disturbance from which Karl formed. The vortex center is determined objectively by first finding the center point that maximizes the azimuthal mean winds within three degrees of the candidate locations at 950 and 700 mb. The vortex center is then taken to be the average
of these two estimates. If maximum 10-m winds exceed tropical storm strength (18 m s\(^{-1}\)) in the model, a Barnes analysis (Barnes 1964) is performed using the 10-m, 850-mb, and 700-mb vorticity fields to find a wind-based storm center. This approach is similar to the Geophysical Fluid Dynamics Laboratory (GFDL) tracker algorithm (Marchok 2010) except that geopotential height and surface pressure data are omitted to avoid complications caused by land in the model.

We first examine the time series of mean relative vorticity near the storm center in the EnKF analyses, which was found in Munsell et al. (2013) to be an important factor in simulating intensity changes for Tropical Storm Erika (2009). Vertical relative vorticity ($\zeta$) is averaged within three degrees of the circulation center at 950 and 500 mb (denoted $\bar{\zeta}$) to estimate the circulation strength at each time (Figs. 2a,b). A broad low-level vortex persists during the early assimilation cycles for each experiment, but decreases during 11–12 September; this is reflected in the 950-mb $\bar{\zeta}$ in Fig. 2a. The dissipation of Karl on 17 September can also be seen from the rapid decrease in 950-mb $\bar{\zeta}$ during the last assimilation cycles, when the simulated storm makes its second landfall on the coast of Mexico. Unlike the low-level vortex, the strength of the 500-mb circulation increases steadily with time until the end of the cycling period (Fig. 2b). The decrease in the low-level circulation between 11–12 September, and steady increase in the mid-level circulation are consistent with Fig. 8b of Davis and Ahijevych (2012), which shows the time evolution of average tangential winds estimated from the PREDICT dropsonde observations.

Observations of the pre-Karl disturbance reveal a large displacement of the low- and mid-level circulation centers in the days preceding genesis (Davis and Ahijevych 2012). Likewise, the EnKF analyses in our experiment contain a large amount of vortex tilt, as defined by
the difference between 950- and 500-mb circulation centers (Fig. 2c). In Fig. 2d, we also
plot the 950- to 500-mb local vertical shear at each time, using winds within three degrees of
the storm center. The local shear takes into account the total effects of environmental shear
and asymmetries induced by the tilted vortex. While the local shear is characterized by
large fluctuations during the days leading up to genesis, the amplitude of these fluctuations
decreases prior to 18 UTC 14 (indicated by the black dashed line in Fig. 2) as the low-
and mid-level circulation centers reach a near vertical alignment (Fig. 2c). Mechanisms by
which a tilted pre-genesis vortex in vertical shear can realign are discussed in Schecter et al.
(2002), Nolan and McGauley (2012) and Rappin and Nolan (2012), and are theorized to be
an important factor in determining when tropical cyclogenesis will occur. Using idealized
simulations, Rappin and Nolan (2012) show that the vertical alignment of the vortex (and
eventual genesis) can be delayed substantially when the tilt is large. A large tilt can also
increase the sensitivity of the genesis forecast to initial conditions, thus decreasing the in-
trinsic predictability of the event (Zhang and Tao 2013). For that matter, the vortex tilt in
the analyses leading up to genesis is expected to have a large influence on the deterministic
and ensemble forecasts, which will be discussed in sections 4 and 5. By including the PRE-
DICT observations in the data assimilation cycles, the EnKF is able to spin up the mid-level
vortex earlier in the cycling and produce a closer alignment between the 950- and 500-mb
circulations leading up to the genesis time.
b. Thermodynamic structure

Thermodynamic variables are compared in the vicinity of the tropical weather system for the same analyses described above. Figure 2e shows the 950−500 mb column relative humidity (CRH, or the ratio of vertically integrated water vapor to vertically integrated saturation water vapor) averaged within three degrees of the designated storm center. All cases show a clear diurnal cycle in CRH leading up to the genesis time. The pre-genesis diurnal signal is consistent with Figure 3b of Davis and Ahijevych (2012), which shows several daily maxima in cloud-top temperatures derived from Geostationary Operational Environmental Satellite (GOES) infrared data between 12 and 15 UTC. Melhauser and Zhang (2013) attribute this convective cycle to a nocturnal destabilization of the near-wave environment brought on by longwave radiative cooling. A similar diurnal signal is found in the 950−500 mb shear (Fig. 2a), except that the daily maxima in shear typically occurs about 12 h after the maxima in CRH. In addition to the diurnal cycle in CRH, Fig. 2e shows an increase in mean CRH values near the center of the storm when PREDICT dropsondes are assimilated.

Average perturbation virtual potential temperature ($\bar{\theta}_v'$) is estimated by taking $\theta_v$ between three and six degrees from the center as the environmental value and subtracting it from the mean $\theta_v$ within three degrees of the center. Vertical profiles are plotted every six hours in Fig. 3 for the same analysis times shown in Fig. 2. Starting from 12 UTC 11 September, both cases produce a warm $\theta_v$ anomaly above 600 mb in the analyses. The upper-level warm anomaly increases steadily in the analyses leading up to genesis, but undergoes no major changes as Karl forms into a tropical storm prior to 15 September and rapidly intensifies.
during 16 and 17 September. Consistent with the higher 500-mb circulation strength (Fig. 2d), the case that uses PREDICT observations yields larger perturbations to $\theta_v$ in the days leading up to genesis (Figs. 3b,c) suggesting that PREDICT observations help accelerate the development of the mid-level vortex.

4. Deterministic forecasts from EnKF analyses

a. Track and intensity

Deterministic forecasts are run from the 13.5-km EnKF mean analyses using a 4.5-km nested domain that follows the storm with the preset moves option in WRF (Figs. 4a-d). The location of the moving nest in the domain comes from 3-h position estimates of the tropical weather system that were determined from 13.5-km forecasts without the nest. Each simulation starts from the respective analysis time and ends shortly after the second landfall time on 00 UTC 18 September. Results are shown for simulations that are initialized between 18 UTC 12 and 00 UTC 15 September to compare the forecast performance in the 48 h leading up to genesis. Simulations that are initialized before 18 UTC 12 September do not capture the vortex alignment that occurs in the analyses between 13 and 14 September (Fig. 2a). We omit forecast results from these times because of the inability of the model to generate a tropical cyclone by the end of the forecast period.

Starting from 12 UTC 13 September, simulations that are initialized from EnKF analyses without PREDICT dropsondes provide reasonable track forecasts for Karl; i.e., they reproduce the southern path of the storm over the Bay of Campeche and a second landfall
on the Mexican coast before 18 September. These simulations also produce a tropical cy-
clone before the end of the forecast period, but have little skill in predicting the timing of
 genesis (Fig. 4b). Though not shown, the number of GOES cloud-top wind observations
increases significantly in the vicinity of the tropical disturbance on 12 UTC 13 September.
The availability of new wind data over the weather system provides the EnKF with enough
information to make accurate position updates to the mid-level circulation, which leads to
the improved track forecasts after this time. In the absence of high-resolution in situ obser-
vations near the tropical weather system, the EnKF-MADIS case provides a storm structure
that is not favorable for genesis until late in the simulations. The simulated disturbance is
slow to develop in the forecasts, owing to the weak circulation and column moisture, and a
displacement (tilt) between the low- and mid-level circulation centers in the analyses (Fig.
2). The only deterministic forecast from these analyses that accurately predicts a land-
falling tropical cyclone for the Yucatan Peninsula is initialized from 12 UTC 14 September,
six hours before the true genesis event occurred.

Figures 4b,d show a large improvement in the intensity forecasts when PREDICT drop-
sondes are included in the set of assimilated observations. One benefit is that all forecasts
that are generated after the 18 UTC 12 September cycle capture the genesis event before
making the second landfall on 17 September. Deterministic forecasts begin to accurately pre-
dict a landfalling tropical storm for the Yucatan Peninsula on 12 UTC 13 September, which
is a 24-h improvement over the control EnKF case in terms of ability to forecast the genesis
event prior to landfall. These simulations more accurately reproduce the rapid intensifica-
tion on 16 September as well, likely because a self-sustained tropical cyclone forms before
entering the Bay of Campeche. The EnKF-PREDICT analyses also produce more accurate
position estimates of the tropical system, indicated by the x's Fig. 1, which translates into improvements in the track forecasts during the early cycles. Because the EnKF maintains a full-physics ensemble of model states throughout the cycling, each analysis allows information from previous assimilation cycles to contribute to the flow-dependent background covariance used during the data assimilation. The analyses in the EnKF-PREDICT case therefore benefit from the additional observations as well as an improved background ensemble at each cycle.

Dropsondes from the PREDICT flight missions have a similar spatial coverage of the pre-genesis disturbance at each time, so the increase in forecast performance after 12 UTC 13 September is expected to come mostly from the changing dynamics of the pre-genesis disturbance leading up to this data assimilation cycle; see Davis and Ahijevych (2012) for a detailed description of the dropsondes at each time.

b. Forecasts from 06 and 12 UTC 13 September

The EnKF-PREDICT experiment produces the first accurate deterministic forecast for the pre-landfall genesis event on 12 UTC 13 September. Forecast data from the 4.5-km grid spacing moving nest are used in this section to compare the vertical structure of the disturbance before and after genesis in the EnKF-MADIS and EnKF-PREDICT data assimilation experiments.

Figures 5a,b show the time series of 950- and 500-mb mean relative vorticity every three hours for forecasts initialized on 06 and 12 UTC 13 September from the pair of analyses. These results are compared with the EnKF-PREDICT analyses (green lines in Fig. 5), which
represent the best estimate of Karl’s kinematic and thermodynamic structure at each forecast time. While the 06 UTC 13 EnKF-PREDICT simulation is slow to amplify the low-level vorticity, the 12 UTC 13 forecast produces the same rapid increase in the surface vortex that is found in the analyses (Fig. 5a). Likewise, forecasts that are initialized from the EnKF-MADIS analyses are slow to increase the low- to mid-level circulation strength with time, thus showing the importance of the PREDICT observations at 12 UTC 13. The stronger circulation aids the disturbance in retaining higher values of 950−500-mb CRH during the hours leading up to genesis (Fig. 5e), which will be shown in section 5 to contribute greatly to Karl’s genesis in ensemble forecasts.

The alignment of the low- and mid-level circulations in the analyses appears to be an important factor in simulating Karl’s development (Figs. 5c,d). The vortex in the 06 UTC 13 September EnKF-PREDICT deterministic forecast is initialized with a 370 km tilt, and intensifies slowly with time (Fig. 5a,b). Nevertheless, the accuracy of the genesis forecasts improves greatly after the vortex tilt in the analyses decreases to 140 km on 12 UTC 13. All EnKF-PREDICT forecasts that are generated after the vortex alignment on 13 September capture the genesis and rapid intensification that follows (Figs. 4d). Despite the decrease in tilt after initialization for the four forecasts examined in Fig. 5, the local vertical shear remains relatively high after 00 UTC 15 September because of an increase in vertical speed shear (not shown).

The stronger vortex that is produced in the EnKF-PREDICT forecasts coincides with a larger $\theta_v$ anomaly in the middle troposphere (Fig 6c,d), owing to the development of a balanced system-scale vortex in the forecasts. The magnitudes of the $\theta_v$ anomalies are greater for the forecast data than the analysis data (comparing Figs. 3 and 6) likely because the
model is allowed to simulate the amplification of the system-scale disturbance and eventual
genesis event with no discontinuities from the data assimilation. This is demonstrated in
the EnKF-PREDICT case by the large increase in upper-level $\bar{\theta}'_v$ during rapid intensification
on 16 September (Fig. 6d). These simulations also produce strong negative perturbations
in surface $\theta_v$ during the late afternoon to evening hours (18 - 00 UTC), which appear as a
much weaker signal in the analysis $\bar{\theta}'_v$ fields. The negative perturbations reflect large-scale
warming away from the storm (cf. Melhauser and Zhang 2013), and not a decrease of $\theta_v$ in
the low-level vortex at these times. The diurnal signal persists throughout the entire length
of the simulations, but it appears more strongly in $\bar{\theta}'_v$ as the tropical cyclone intensifies and
causes the inner three degrees of the verificaiton region to become less sensitive to diurnal
changes in radiation.

c. The development of Karl in the 12 UTC 13 September simulations

Figure 7 provides a more detailed comparison of the 12 UTC 13 September analyses
with and without the PREDICT observations. Each plot uses system-relative streamlines
to show the flow field following the pre-genesis disturbance. The streamlines are estimated
by subtracting a 6-h storm motion vector from each wind field. A two-dimensional low-pass
filter is then used to remove wavelengths smaller than 150 km to compare the “system-
scale” winds near the disturbance. The EnKF-MADIS case produces a 500-mb vortex near
the same location as in the EnKF-PREDICT case (Figs. 7a,e). Nevertheless, the 950-mb
vortex is located much farther behind the 500-mb cyclone in the EnKF-MADIS analysis. The
close agreement between the 500-mb vortex locations in the two experiments may be due
to the availability of GOES wind vectors at this time (not shown), though the circulation of the mid-level cyclone is much greater when the PREDICT observations are included (Fig. 5d). 850-mb streamlines and unfiltered $\zeta$ are plotted in Figs. 7d,h along with system-relative wind vectors from the analyses and PREDICT dropsondes. The comparison between observed and analysis wind vectors at this time verifies the larger vortex position error in the EnKF-MADIS case, and demonstrates the role of PREDICT observations in representing the low-level circulation beneath the mid-level vortex. These wind vectors also indicate that the position of the vortex in the EnKF-PREDICT analysis remains displaced westward of the true vortex position at this time, despite the assimilation of additional observations. When performing the data assimilation, the EnKF relies on a sparse set of observations, relative to the state space, and imperfect estimates of forecast error covariance to move the vortex and correct its intensity. Nevertheless, the resulting analysis reproduces several features of the pre-genesis disturbance that favor Karl’s future genesis, even if the position of the system-scale vortex is imperfect.

In addition to capturing the low- and mid-level vortex alignment, the EnKF-PREDICT analysis contains higher equivalent potential temperature ($\theta_e$) and CRH near the low-level circulation (Figs. 5b,c,f,g), which favors organized deep convection near the surface low. The EnKF-MADIS case contains relatively high values of CRH in the southwest portion of the cyclone, but most of the eastern part of the circulation is exposed to dry air at this time. Both sets of analyses contain slightly lower-than-observed CRH away from the main circulation center when verified with the PREDICT dropsondes (shaded circles in Figs. 5c,g). The presence of dry air within the storm-relative recirculation region may have slowed the early development of Karl in the EnKF-PREDICT simulations, causing the 18-h lag in
forecasting tropical-storm force winds for simulations that are initialized between 12 UTC 13 and 18 UTC 14 September.

Forecasts that are initialized from the two EnKF analyses in Fig. 7 are compared in Fig. 8. Genesis occurs near 12 UTC 15 September in the simulation that is initialized from the EnKF-PREDICT analysis, while the EnKF-MADIS case fails to produce a tropical cyclone during the same forecast period. Filtered system-relative streamlines are plotted every 12 h from 00 UTC 14 to 12 UTC 15 September at 950 and 500 mb along with positive values of unfiltered 950-mb $\zeta$. The 950-mb circulation in the EnKF-MADIS forecast remains weak after initialization (Fig. 5c) and lags behind the mid-level circulation in the days leading up to the genesis time. Likewise, the 950-mb circulation in the EnKF-PREDICT simulation moves closer to the 500-mb cyclone and intensifies with time. The forecast from this analysis also contains a noticeably higher number of mesoscale vorticity anomalies 24 h into the simulation that increase in size as the simulation approaches the genesis time.

A scale separation of the 950-mb vorticity and divergence is performed on the forecast data to compare the development of the low-level cyclone before and after genesis in the two cases. As in Fang and Zhang (2011) the scales are organized into three categories: the main system-scale vortex ($L > 150$ km), the intermediate or cluster scale ($50$ km $< L < 150$ km) and the cloud scale, which is made up of individual convective cells ($L < 50$ km). The spectral energy (amplitude) of the scale-separated vorticity and divergence is averaged within three degrees of the circulation center every three hours from the 4.5-km nested domain. Figure 9 compares the amplitude changes in the vorticity and divergence fields over time. While the amplitudes undergo many fluctuations throughout the forecast period, the vorticity and divergence steadily increase with time until the last hours of the
simulation, owing to an increase in positive vorticity and convergence. Both forecasts produce a large spike in the initial convective-scale energy as the model adjusts to instabilities that are introduced during the data assimilation. After the initial adjustment, the energy in the convective-scale vorticity increases slowly to the end of the forecast period. Likewise, the energy in the intermediate- and system-scale vorticity also amplifies over the forecast period. The EnKF-PREDICT simulation, however, strengthens the larger scale vorticity field at a faster rate than the EnKF-MADIS case. In the first 48 h of the EnKF-PREDICT simulation, the energy in the vorticity field increases at a rate that is unmatched by the divergence field; i.e., the flow becomes increasingly more rotational leading up to genesis. Fang and Zhang (2011) propose that the development of the low-level vortex follows from the convergence of large-scale or convectively-generated vorticity toward the center of the system-scale cyclone. For the development of Hurricane Dolly (2008) they showed that the Rossby radius of deformation could decrease to values that are smaller or comparable to the system scale as the low-level vortex intensifies. The convective-scale diabatic heating can be effectively trapped by the system-scale circulation in the pre-genesis disturbance as the flow in the system-scale vortex approaches geostrophic balance. The two simulations compared in Fig. 9 contain minor differences in the early production of small-scale vorticity, likely due to the larger column moisture in the EnKF-PREDICT simulation. Nevertheless, the initial intermediate- and system-scale vorticity in these two cases differ by a factor of two. The EnKF-MADIS simulation appears to lack a sufficiently strong system-scale circulation to protect the near-wave air from the relatively dry environment (Dunkerton et al. 2009), or as described by Fang and Zhang (2011), organize the small- and intermediate-scale vorticity anomalies and amplify the system-scale vortex. This can be seen from the lack of
intermediate-scale development and the smaller production of vorticity at the cloud scale in the EnKF-MADIS forecast. Though not shown, this is also true for forecasts that are initialized prior to 12 UTC 13 September that did not capture the genesis before the initial landfall.

5. Ensemble forecasts from EnKF analyses

One conclusion from the cycling data assimilation experiments is that deterministic forecasts that are initialized before 12 UTC 13 September fail to produce the genesis event in the EnKF-PREDICT case. Using ensemble forecasts from 12 UTC 12 September, Torn and Cook (2013) found the development of Karl to be most sensitive to the initial circulation in the lower troposphere. For that matter, we hypothesize that the stronger low-level circulation induced by the PREDICT observations at this cycle creates conditions that are more favorable for genesis. To investigate this result, ensemble forecasts are run from 06 and 12 UTC 13 September to quantify changes in the probabilistic forecasts before and during the first cycle that successfully predicts the genesis event. These forecasts are initialized from the 13.5-km EnKF-MADIS and EnKF-PREDICT analyses and do not use a 4.5-km nested domain. To distinguish between developing and non-developing members, we define a developing member to be a simulation that contains maximum 10-m winds > 18 m s\(^{-1}\) (tropical-storm strength) for three consecutive three-hour time stamps between 18 UTC 14 and 00 UTC 16. This criterion limits the developing cases to members that form and maintain a tropical cyclone before making landfall on the Yucatan Peninsula.

The EnKF-MADIS and EnKF-PREDICT ensemble analyses at 06 UTC 13 September
produce a similar number of developing forecast members (20 and 22, respectively) as indicated by the red (developing) and blue (non-developing) lines in Fig. 10. While a larger intensity spread is observed for the case that does not use the PREDICT observations, the two ensembles provide similar probabilistic forecasts for genesis at this time. The ensemble forecasts suggest that a potential for genesis exists, even before the deterministic forecasts predict Karl’s development. In the next analysis cycle at 12 UTC 13, the number of developing members for the EnKF-MADIS case increases from 20 to 26, while the developing members in the EnKF-PREDICT case increases more substantially from 22 to 44 (comparing Figs. 10 and 11). The change in genesis probability between 06 and 12 UTC therefore agrees with the deterministic forecast results in Fig. 4. As mentioned earlier, a larger-than-average number of upper-level satellite winds are available during the 12 UTC 13 September cycle, which may have contributed to the modest increase in predictability at this time for the EnKF-MADIS case. Nevertheless, the large increase in genesis probability for the EnKF-PREDICT case comes mostly from additional dropsondes that were collected from a midday flight mission on 13 September. Both of these factors may have also led to the observed reduction in storm track uncertainty in these analyses and forecasts.

The field observations were shown in the previous sections to increase the system-scale circulation at low-to-mid levels of the ensemble mean analysis, which contributes to the development of the tropical cyclone in the deterministic forecast. To understand how this result affects the ensemble forecasts, vertical profiles of system-scale mean $\zeta$ are estimated for the EnKF-PREDICT ensemble to compare the circulation strength between developing and non-developing members. A two-dimensional low-pass filter is applied to remove features with wavelengths smaller than 150 km from the $\zeta$ field, and values are averaged within three
degrees of the circulation center every 25 mb from the surface to 500 mb. The mean $\zeta$
profiles are plotted for ensemble members at the 06 and 12 UTC 13 analysis times (Figs. 12a,c) and for the 6-h ensemble forecast from 06 UTC 12 (Fig. 12b). As in Figs. 10 and 11, the red and blue lines indicate the developing and non-developing members, respectively. In agreement with the deterministic forecasts, members that are initialized with larger system-scale circulation between the surface and 600 mb are more likely to produce a tropical cyclone before the first landfall time. The increase in mean $\zeta$ going from 06 to 12 UTC 13 is most substantial below 700 mb in the ensemble members, where the PREDICT observations are assumed to have the largest impact, owing to the lack of low-level satellite winds. It is also worth noting that the spin up of the low-level cyclone using PREDICT dropsondes is inherently linked to vortex tilt, as the strong 950-mb vortices in the EnKF-PREDICT ensemble analyses are located close to the 500-mb center at this time (Fig. 7).

6. Impact of model resolution on EnKF analyses and forecasts

This section describes a third data assimilation experiment that examines the effects of model resolution on the EnKF analyses. We repeated the EnKF-PREDICT case using a nested 253 x 253 domain with 4.5-km grid spacing during the ensemble forecast and analysis steps of the data assimilation cycles (denoted EnKF-4.5km). Given that 4.5-km grid spacing can more accurately represent the effects of convective-scale features in the model, our early hypothesis was that a high-resolution ensemble might improve the background
error covariance estimate between cycles, thus making the data assimilation more effective.

To verify the high-resolution analysis results, the time series of 950–500 shear, tilt, CRH, and average $\zeta$ are compared with analyses from the previous two experiments in Fig. 2. The higher resolution data assimilation has little noticeable effects on the location and magnitude of the low- and mid-level circulation leading up to genesis, and obtains the same estimate of integrated moisture near the circulation center as the lower-resolution EnKF-PREDICT case. While the EnKF-4.5km experiment produces a slightly larger upper-level $\theta_v$ anomaly in the storm center before and after genesis (Fig. 3c), the differences in thermodynamic structure remain relatively small between the two PREDICT cases. Likewise, the higher-resolution data assimilation produces little improvement in deterministic track and intensity forecasts leading up to genesis (Figs. 4e,f). It follows that the model resolution used in the EnKF-MADIS and EnKF-PREDICT experiments is sufficient for capturing the features of the pre-genesis disturbance and surrounding environment that lead to the formation of Karl. This result is not surprising, considering that the role of vorticity at scales larger than the convective and intermediate scales was shown in Figs. 9 and 12 to be instrumental to Karl’s development. The accuracy of the analyses may also be limited to the meso-$\alpha$ or meso-$\beta$ scales in our experiments, given the spatial and temporal frequency of observations and possible limitations in the applied data assimilation method.

7. Conclusions

This study investigates the predictability of a tropical cyclogenesis event using an EnKF data assimilation system that was applied in real time during the PREDICT field campaign.
Cycling data assimilation experiments are performed over a ten-day period in which Hurricane Karl formed, rapidly intensified into a category-three hurricane and dissipated over the Mexican coast. One set of analyses uses routinely collected observations from MADIS, while a second set uses both MADIS and PREDICT observations. The EnKF analyses that take into account PREDICT dropsondes provide a detailed four-dimensional dataset, which is used for examining the factors that led to Karl’s genesis. Deterministic and ensemble forecasts from these analyses are also used to examine the role of initial-condition errors in predicting genesis.

Our results show that the PREDICT observations improve significantly the conditions for genesis in the analyses. The additional dropsonde measurements increase the system-scale vortex strength in the lower and middle levels, while reducing the displacement between the low- and mid-level circulation centers. They also produce larger warm temperature anomalies in the system-scale vortex and increase the integrated moisture between 950 and 500 mb. These factors yield a 24-h increase in lead time for predicting the genesis of Karl from deterministic forecasts. The largest change in Karl’s predictability occurs on 12 UTC 13 September during cycling, owing to the alignment of the low- and mid-level cyclones and the strength of the low-level circulation in the ensemble mean analyses. A PREDICT flight mission at this time provided the additional observations that were necessary for improving the deterministic and probabilistic forecasts for the genesis event. While the largest contribution of these observations is found at the mesoscale, synoptic-scale differences between our data assimilation experiments cannot be ruled out, given the spatial coverage of the dropsondes and the 900-km radius of influence that is used by the EnKF.

We performed an additional data assimilation experiment to examine the impact of model
grid spacing on analyses near the tropical weather system. This experiment uses a configuration that is identical to the previous experiments, except that a nested 4.5-km grid spacing domain is applied during the ensemble forecast and analysis steps of the cycling. The nested analyses yield marginal changes in the kinematic and thermodynamic structure of the disturbance, but no systematic improvements in the deterministic forecasts for the genesis event. This result suggests that initial condition errors at the meso-α and meso-β scales still pose large challenges for predicting genesis. We suspect that an improved observation network or targeted observations of the pre-genesis disturbance can decrease the initial condition errors at these scales. Advanced four-dimensional or hybrid data assimilation methods and more efficient assimilation of remotely-sensed observations may also be required before large gains can be made in predicting when and where tropical cyclones form.

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