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2017 Coastal Master Plan Implementing

Appendix C – Modeling
Attachment C3-3

Storm Effects in the ICM Boundary Conditions

Report: Version I

Date: July 2015

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Coastal Protection and Restoration Authority

This document was prepared in support of the 2017 Coastal Master Plan being prepared by the Coastal Protection and Restoration Authority (CPRA). The CPRA was established by the Louisiana Legislature in response to Hurricanes Katrina and Rita through Act 8 of the First Extraordinary Session of 2005. Act 8 of the First Extraordinary Session of 2005 expanded the membership, duties and responsibilities of the CPRA and charged the new Authority to develop and implement a comprehensive coastal protection plan, consisting of a Master Plan (revised every 5 years) and annual plans. The CPRA's mandate is to develop, implement and enforce a comprehensive coastal protection and restoration Master Plan.

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Executive Summary

In preparation for the 2017 Coastal Master Plan, an Integrated Compartment Model (ICM) was developed to approximate the long-term geomorphic evolution of the Louisiana coast. Improvements in the ability of landscape models to account for hurricane impact on coastal morphology were tested, for which hurricane boundary conditions were required. Boundary conditions representing the hurricane history over the past 50 years was needed. While a basic historic record of storm occurrence is available for the Louisiana coast, the archive of historic data was not adequate to provide the level of detail required as input to the ICM. Due to the sparse and inconsistent availability of real wind, surge, and wave data for the previous 50 years, boundary conditions for the ICM were derived from an existing set of synthetic hurricane simulations, for which detailed wind, surge, and wave data was readily available at the spatial and temporal resolution required. Each historical storm was aligned with an individual storm in the synthetic storm suite according to the approximate comparison of meteorological storm parameters. While synthetic storms do not exactly match all the details of their historical counterpart, the ICM are being evaluated for prediction of long-term trends for which the ensemble effects of all the storms are more important than the accuracy of any of the discrete events in particular. This report describes the existing synthetic storm data, explains the methodology used to select appropriate storms to represent the actual 50-year hurricane history, and clarifies the benefits and limitations of this approach for approximating the historic record.

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List of Abbreviations

Acronym	Term
ADCIRC	Advanced Circulation Model
AH	approximated history
Cp	central pressure
CPRA	Coastal Protection and Restoration Authority
CLARA	Coastal Louisiana Risk Assessment Model
ENSO/AMO	El Niño-Southern Oscillation/Atlantic Multi-decadal Oscillation
FEMA	Federal Emergency Management Agency
ICM	Integrated Compartment Model
JPM-OC	Joint Probability Model- Optimal Sampling
PBL	Planetary Boundary Layer
R	radius of maximum winds
SWAN	Simulating Waves Nearshore
TRMM	Tropical Rainfall Measuring Mission
USACE	United States Army Corps of Engineers
Vf	forward speed of the storm

1.0 Project Overview

As part of the landscape modeling performed during the 2012 Coastal Master Plan, the effects of tropical storms and hurricanes were included in only a few aspects of landscape dynamics. For instance, sediment deposition by hurricanes in coastal marshes was assumed to occur at a constant annual average rate. Other effects of storms, such as destruction by barrier island erosion/overwash and wetland substrate damage, could not be reflected in the analysis due to limitations in the modeling approach used. In preparation for the 2017 Coastal Master Plan, improvements to the ability of landscape models to reflect hurricane storm impacts are being pursued. While a basic historic record of storm occurrence is available for the Louisiana coast, the archive of historic data is not adequate to provide the level of detail required as input to the landscape models. For instance, data for wind conditions, surge levels, wave heights, and precipitation are only available at sparse gauge locations that do not coincide with the locations where data is needed for the landscape model boundaries. Moreover, data fidelity decreases for older storm events, thus data from 50 yeas ago has significant uncertainty. To support model testing and development, this effort was designed to develop a realistic dataset of hurricane forcing that can improve the boundary conditions for the Integrated Compartment Model (ICM). The updated boundary conditions are required to represent the hurricane history over the past 50 years and are used to approximate landscape evolution during the future 50-year period. Due to the limitations of historic data, the boundary conditions for the ICM were derived from an existing set of synthetic hurricane simulations, for which detailed wind, surge, and wave data is readily available at the spatial and temporal resolution required for the ICM forcing. This report describes the existing synthetic storm data, explains the methodology used to select appropriate storms to represent the actual 50-year hurricane history, and clarifies the benefits and limitations of this approach to approximating the historic record.

To accomplish this goal, the following tasks were performed:

1. Examine characteristics of tropical cyclones in the selected 50-year historical record (1963-2012), and inventory the existing Joint Probability Method-Optimal Sampling (JPM-OS) synthetic storm suite (446 storms) to identify threshold characteristics defining a "storm" that can be used in the landscape models.
2. Identify spatial and temporal patterns of historic storms for the Louisiana coast.
3. Select historical storms to be considered in the landscape model and align each historical storm with an individual synthetic storm from the JPM-OS storm suite to approximate the 50-year historic storm record.
4. Estimate precipitation distribution and volume for each synthetic storm used with the ICM. Methodology parallels previous Coastal Louisiana Risk Assessment Model (CLARA) and LACPR estimations for precipitation. Precipitation data for the storm events are compared to the non-storm data to ensure consistency.
5. Create three optional combinations of matching synthetic storms to reflect historic alternatives.

Outcomes of this effort are:

1. A representative history of hurricanes using JPM-OS synthetic storms to approximate real storms.

2. Time series of wind, water level, and waves, from ADCIRC and SWAN simulations of the representative JPM-OS storms. Data were provided at CPRA-specified locations per event to be stitched in the 50-year records and serve as the new boundary and forcing condition for the improved landscape models.

3. Precipitation estimate in time and space per event.

4. Optional 50-year histories using similar JPM-OS storms re-distributed in time and space.

2.0 Data and Method

2.1 Historical and Synthetic Storm Data

Identifying the historic record for the Louisiana coast was performed by examining storm events from two datasets; the Atlantic hurricane database HURDAT2 (Landsea et al., 2014) and the JPM-OS synthetic storm suite (USACE, 2008). First, the HURDAT2 dataset was used to characterize historical storms (including both tropical storms and hurricanes) that made landfall along the central, northern Gulf Coast and generated significant surge and waves along coastal Louisiana. In order to select appropriate storms from the comprehensive HURDAT2 record, it was necessary to create criteria to identify storms significant to the Louisiana coast. According to Keim and Muller (2009), winds of at least tropical storm strength can extend as much as 150 miles from the center of a Category 3-5 hurricane, Figure A (Appendix A). This provides a criterion for selecting storms from the HURDAT2 data base that may potentially impact the Louisiana coast. Therefore, storms that pass within 2.5 longitude degrees of a target location, e.g. Louisiana coast, compose the dataset from which historical storm characteristics in time and space were extracted. Initial inventory of historic storms with potential for impact on the Louisiana coast are listed in Appendix B (Table B). The values of central pressure, maximum wind, and forward speed listed in the tables for each historical event were extracted along the storm tracks between 28.5° to 31°, which reflect the dynamics of each storm close to the coast which guided storm matching from the JPM-OS storm suite. In total, 49 hurricanes (60%) and 28 tropical storms (40%) made landfall or otherwise affected coastal Louisiana. Of the 49 hurricanes, 45% were major hurricanes. Note that the storm categories were determined using wind speed (Appendix B), which may not be the maximum speed over the entire history of the storm event.

Each of the identified historic storms listed in Appendix B were approximated by one of the synthetic storms in the JPM-OS storm suite. The JPM-OS storm suite was originally developed by the United States Army Corps of Engineers (USACE) for the Federal Emergency Management Agency (FEMA) to represent probabilistic hurricanes along the Louisiana coast (USACE, 2008). The JPM-OS storm suite has a total of 446 synthetic storms on 46 distinct storm tracks with a range of forward speed (6 knots, 11 knots, and 17 knots), central pressure (900mb, 930mb, 960mb and 975mb), radius of maximum winds (6nm – 35.6nm), and maximum wind speed (67 knots – 113 knots). Note that the JPM-OS storm suite does not include very low-intensity storms such as tropical storms, thus is not able to represent the historical record of tropical storms. However, the JPM-OS synthetic storms do cover the range of hurricane-strength storms and does adequately represent the actual historic storms identified for the Louisiana coast. Appendix C provides storm tracks, track IDs, corresponding JPM-OS storm number and the range of parameters for the synthetic suite.

2.2 Hypothetical Histories of Storm Events

Because of the limited availability of meteorological and ocean data for actual storm history over the past 50-years, data provides limited utility as boundary conditions for the ICM. Synthetic storms capture the primary dynamics of tropical cyclones and provide a rich dataset in space and time for many of the variables needed as ICM boundary conditions. Realistic datasets of hurricane forcing composed of synthetic storms can be used by the ICM in various domains and examine future scenarios. This report documents the methodology for selecting synthetic storms to represent historical storms.

First, each of the selected historical storms were aligned with one of the synthetic storms. The composite of all identified synthetic storms constitute an approximation of the historic hurricane record. The alignment of storms from the JPM-OS synthetic storm suite is as follows:

1. Select the best match to historical track from the set of synthetic storm tracks in terms of angle and landfall location.
2. Select candidate synthetic storms that closely match the central pressure of a historical storm.
3. From the candidates, select the best match (in order of importance) to forward speed, storm size, and maximum wind.
4. If multiple candidates are identified in step 1 through 3, review storm surge response and select storm that produces the most similar surge response.

Second, hypothetical histories that may have occurred were created to explore some potential variations to the historical record. For instance, variations in landfall location of individual storms and variations of storm decadal frequency are explored. The goal of this effort was not to explore alternate histories that deviate from the real history in a statistically significant way. Specifically, alternative hypothetical histories do not consider climate change scenarios where storms may be significantly more frequent in general, or where storms may be significantly more intense. Rather, the goal is to generate hypothetical histories with a similar overall probability of occurrence. The assumption is made here that by simply rearranging the landfall location and temporal order of the actual storms while maintaining a similar number of total storms over the 50-year period and the same characteristics of the individual storms, the resulting combinations of storm events have a similar probability of occurrence as the original combination.

In total four synthetic storm combinations are envisioned to represent four alternative histories. The first combination is intended to match the actual ordering of historical storms as they actually occurred, and is denoted as AH1. The second and third alternatives are two hypothetical histories denoted as AH2 and AH3, which represent a slight bias of more storms to the west and east, respectively. The fourth alternative is denoted as AH4 representing a bias of more storms occurring during the last two decades of the 20th century and fewer in the 21st century. Particularly, six storms (26%) were redistributed to create AH2, AH3, and AH4 in comparison to the approximated history (AH1). In AH2 and AH3, storms that were redistributed were aligned with a new set of synthetic storms that retain the same values of dynamic storm parameters but have different tracks with desired landfall locations from those in AH1. For AH4, some of the storms are shifted in time, but all of them are fixed in space. Thus, all of the JPM-OS analogs in AH1 are re-used in AH4.

2.3 Precipitation

Real precipitation data during hurricane events is inadequately rich to supply boundary condition data to the ICM. For use in the ICM, it is more important to have realistic spatial and temporal coverage over the complete history than it is to have a detailed replication of a single event. Thus, in the absence of measured precipitation data for all of the storms, a consistent method for approximating precipitation was used for each of the synthetic storms selected to represent a historical event.

Precipitation estimates for each representative synthetic storm event were calculated using the method applied by RAND during the 2012 Master Plan for CPRA (Johnson et al., 2013). Precipitation data for the ICM were approximated from the precipitation model to correspond to individual synthetic storm scenarios. The methodology applied by RAND was based upon the risk and reliability model previously used by IPET (Ebersole et al., 2007). This approach is an approximation of a relationship developed by Lonfat, Marks, and Chen (2004) based on hurricane observations from the Tropical Rainfall Measuring Mission (TRMM). In this method, the baseline rainfall rate is assumed to be a linear function of pressure deficit (ΔP) inside the radius of maximum wind speed (R_{max}) and to exponentially decay with distance beyond R_{max}. This is written:

$$I = 1.14 + 0.12\Delta P \; for \; r \leq R_{max}$$

$$I = (1.14 + 0.12\Delta P) \cdot \exp\left[-0.3 \cdot \left(\frac{r - R_{max}}{R_{max}}\right)\right] for \; r > R_{max}$$

I	[mm/hr]	Rainfall intensity
ΔP	[mbar]	Pressure deficit (difference between standard atmospheric and local pressures)
r	[km]	Distance from center of storm to location
R_{max}	[km]	Radius of maximum wind speed

Based on TRMM observations, Lonfat, Marks, and Chen (2004) demonstrate that rainfall intensity varies from quadrant to quadrant around the storm center. To account for this, the IPET analysis included a multiplier of 1.5 for rainfall intensity at points to the right of the storm track (the azimuth) and 1.0 for rainfall intensity at points to the left of the storm track (Ebersole et al., 2007). The same approximation was employed in this study. There are other precipitation models available that consider rainfall dependence upon more storm parameters, such as forward speed, track angle, and surface drag. Note that primary consideration for the precipitation component of this effort is to maintain consistency with previous work performed on behalf of CPRA and The Water Institute. To avoid incompatibility with precipitation estimates applied in other components of the master plan work, improvements or updates to the methodology were not part of this effort.

To implement this methodology, a FORTRAN code was developed to calculate rainfall estimates at points of interest along the Louisiana coast for any synthetic storm. Using the storm wind and pressure derived from the Planetary Boundary Layer (PBL) model (USACE, 2008), rainfall intensity can be determined at a given location with an interval of 15 minutes or longer, i.e. 1 hour throughout the storm duration. The time series of rainfall intensity can be numerically integrated to provide an estimate of cumulative amount of rainfall (unit in inch) during the storm.

3.0 Approximate History

3.1 Storm Threshold

The appropriate synthetic storm for representing each historical storm is selected according to how well the synthetic storm matches the known meteorology of the historic storm. For many of the older storms, details of surge and wave response to the historical storms are not well known at the locations of interest. Thus, large scale meteorology is a better indicator of which synthetic storms match the historical storms than surge, inundation, or wave heights. In addition to the physical track of a storm, four dynamic parameters are often used to describe a storm event, including (1) central pressure (Cp), (2) the radius of maximum winds (R), (3) forward speed of the storm (Vf), and (4) direction of storm motion (θ). The direction of storm motion is the azimuth angle of the storm track. The central pressure is an indicator of storm intensity and the radius of maximum winds is an indication of the storm size (Ho et al., 1987). The most important factor in storm surge modeling is the intensity of the hurricane, which is directly related to its central pressure (Harris 1959; Ho et al. 1987). To the degree possible, these meteorological characteristics were used to identify storm events in the synthetic storm suite that approximate the historical storms. Surge and wave conditions from the ADCIRC and SWAN simulations for each of the selected synthetic storms were used to supply boundary conditions for the ICM.

Studies have been conducted to examine the climatological probability distribution of these parameters along the Gulf Coast (Ho et al., 1987; USACE, 2008), where three relationships were identified based on historical storm records. In the flood insurance study for southern Louisiana (USACE, 2008) it was documented that: 1), central pressure is related to radius of maximum winds; 2) forward speed is is also related to track azimuth; 3) the maximum wind speed and the wind field is determined by the pressure distribution through a balanced wind model (Myers, 1954; Holland, 2008; USACE, 2008). Thus, out of five major storm characteristics, the storm track, central pressure, and forward speed are three independent, important variables, which can be considered as the primary criteria for differentiating storms.

In order to identify an analogue of a historical storm from the JPM-OS storm suite, the threshold value for preferring historical storms considered in the ICM need compromise to be applicable to the range of dynamics of synthetic storms. The existing JPM-OS storm suite includes only storms that attain a central pressure of 975 mbar or lower. Technically speaking, synthetic storms in the existing suite are not able to very well represent a historical storm attaining a central pressure higher than that. However, many low-intensity storms (tropical storms or Category 1 storms) listed in Appendix B show the minimal or landfall central pressures higher than 975 mbar. Although the absence of tropical storms is a limitation of using the synthetic storm suite, a reasonable cutoff of the central pressure was made to include as many historical low-intensity storms as possible. According to the consideration of the wind speed computed from a balanced wind model (Ho et al., 1987), a central pressure of 982 mbar is estimated if the cyclostrophic wind speed at the radius of maximum wind is the wind speed required for classification as a hurricane. Therefore 982 mbar was used to put a specific bound on the storm selection. It is not intended to be used as a forecasting criterion to distinguish hurricanes from tropical storms. Storms that attain a central pressure of 982 mbar or lower within the latitudes 28.5°-31.0° were approximated by synthetic storms. Even though the upper limit on central pressure is 975 mbar in the synthetic storm set, comparison of storms up to 982 mbar were made to see if track and wind speed of any synthetic storms compare adequately to historical storms near landfall.

3.2 Subset of Historical Storms (1963-2012)

To focus on the most recent 50 years of data, storm events that occurred before 1962 are excluded from the initial list (Appendix B). According to the threshold of central pressure, storms attaining a minimum central pressure higher than 982 mbar would be excluded. However, in order to be inclusive, a set of storms with central pressure as high as 989 mbar are retained in the preliminary analysis of storm trends and are documented in this report. Impacts of each storm on coastal Louisiana were reviewed individually, regarding rainfall, wind strength speed, flooding, the landfall location, and the degree of the impacts based on documents on historical tropical cyclones in the Gulf (USACE, 1972; USACE, 1985; USACE, 2005; Roth, 2010; Landsea, 2014) and http://en.Wikipedia.org.

After removing storms prior to 1962 or with a minimum central pressure higher than 989 mbar, a total of 33 storms remain for alignment with synthetic storms. Of the remaining 33 storms, the magnitude of surge generated along the Louisiana coast was examined as a secondary indicator of storm relevance to the ICM models. Based on historical reports such as USACE, 1972; USACE, 1985; USACE, 2005; Roth, 2010; and Landsea, 2014, hurricanes Ceilia (1970), Frederic (1979), Alicia (1983), Elena (1985), Claudette (2003), Ivan (2004), Dennis (2005), Chantal (1989), Jerry (1989) and Earl (1998) are eliminated due to only minor surge along the Louisiana coast. The major impacts of the storms listed above were concentrated in adjacent states beyond the extent of the ICM model domains. Tropical Storm Fern (1971) is also eliminated because its unusually irregular track cannot be matched to any of the tracks in the JPM-OS storm suite. As a result, 15 storms attaining a central pressure of 982 or lower and 7 storms attaining a central pressure of 983 mbar to 989 mbar are retained and approximated by synthetic storms, and used to express the historic record of hurricane impacts between 1963 and 2012. These storms are listed in Table 1. To concentrate on the time history of a storm when it was approaching the coastline, the parameter values listed in Table 1 are averaged within the latitudes 28.5°-31.0°. The category is defined according to the maximum wind as the storm moved within the latitudes 28.5°-31.0° and thus may not reflect the maximum throughout the entire storm history. The forward speed for each historical storm is averaged over the same 2.5° latitude region to identify the speed near the time of landfall. Note that the forward speed of synthetic storms is constant while historical events present varying forward speeds and can include time periods of extremely slow or lull movement. For this reason, the forward speed at the time of landfall was used when attempting to match synthetic storms. Also note that the synthetic storms are derived from a PBL model, which calculates maximum wind speed from central pressure. There are some historical storms that have higher maximum wind speeds than can be generated by the PBL-based storms. While these limitations prevent an exact match between the synthetic storms and their more complex historical counterparts, the goal is not to exactly reproduce the historical record. Rather the goal is to approximate the historic record with much denser data than would be available using the sparse gauge data. In this manner, the ICM performance can be evaluated over a hypothetical 50-year future using storm dynamics that are similar to the past 50 years of storm dynamics.

Table 1. Subset of Historical Storms (1963-2012)

#	Name	Year	Category	Minimal Cp (mbar) (28.5°-31°)	Vf (knots)	Maximum Wind (knots)
1	Hilda	1964	H3	941	10	100
2	Betsy	1965	H4-5	941	16	135
3	Camille	1969	H4-5	900	13	150
4	Edith	1971	H2	943	17	85
5	Carmen	1974	H4-5	937	8	130
6	Bob	1979	H1	986	17	65
7	Danny	1985	H1	987	11	80
8	Juan	1985	H1	971	7	75
9	Florence	1988	H1	982	12	70
10	Andrew	1992	H4-5	937	9	125
11	Opal	1995	H3	916	21	110
12	Danny	1997	H1	984	3	70
13	Georges	1998	H2	961	4	95
14	Isidore	2002	TS	960	14	55
15	Lili	2002	H3	938	13	105
16	Katrina	2005	H4-5	913	15	125
17	Rita	2005	H3	895	11	105
18	Humberto	2007	H1	985	9	80
19	Gustav	2008	H2	954	13	95
20	Ike	2008	H2	944	12	95
21	Ida	2009	H1	975	8	75
22	Lee	2011	TS	986	5	50
23	Isaac	2012	H1	965	6	70

Figure 1 shows the historical storm strikes listed in Table 1. In Figure 1, a geographic reference line indicated by a solid black line is used to count the occurrence frequency of historical hurricanes that impact each geographic interval of the coast. In total there are 13 segments with the "1" representing western Louisiana state boundary to Texas, "12" representing Gulfport, MS to

Alabama, and "13" representing the bird's foot. For each segment, the number of storm occurrences was counted as the number of storm strikes that fell in the range. It is shown that more hurricanes made landfall from central to eastern coastal Louisiana. To capture this feature, this spatial pattern is illustrated by a relative chance of occurrence, which is defined as the number of occurrences for each segment normalized by the maximum number of occurrence of all segments in coastal Louisiana. For example, the relative chance of occurrences along segment #8 is unity because this is the location most frequently hit.

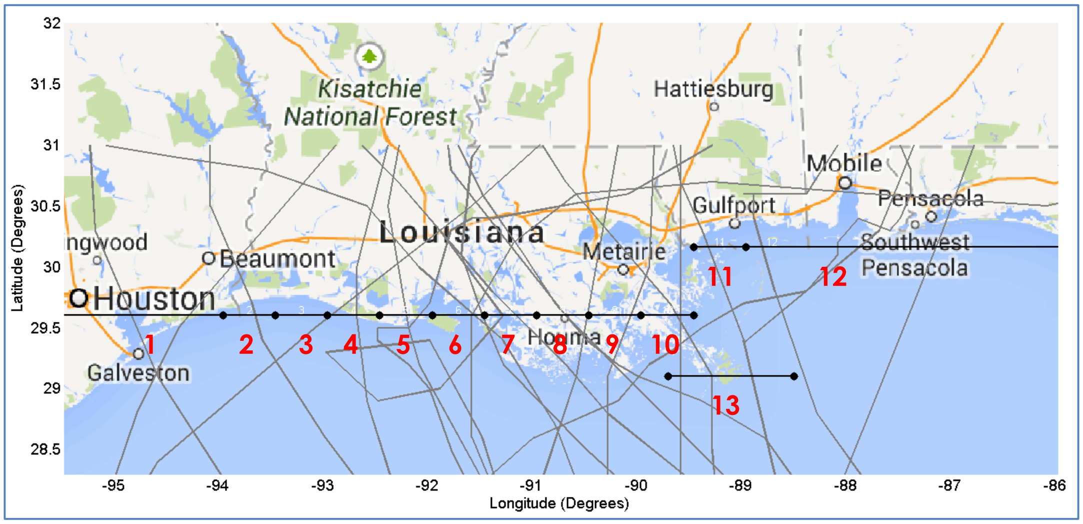

Figure 1. Historical Storm Strikes (1963-2012).
Note: Gray: storms events; black: a geographic reference line (increment #1-12 represents the coast from west to east; increment# 13 represents the bird's foot).

Figure 2 shows the relative chance of occurrence along the coast. The trend aligns well with the documented historical hurricane distribution along the Gulf Coast in terms of return years, i.e. Figure 3 shows the return period (in years) of historical hurricanes (1900-2010) along the coast. In southeastern Louisiana, i.e. Terrebonne, Lafourche and the bird's foot delta, the return periods are seven to eight years while in other places the return periods are relatively longer; i.e. 10-14 years. Note the number of occurrences at increment # 1 and 12 is relatively large because those two segments extend further to the west and east, respectively, including potential storms impacting coastal Louisiana. These storms were aligned with synthetic storms to form the first realistic dataset of hurricane forcing input to the ICM, the approximated history (AH1).

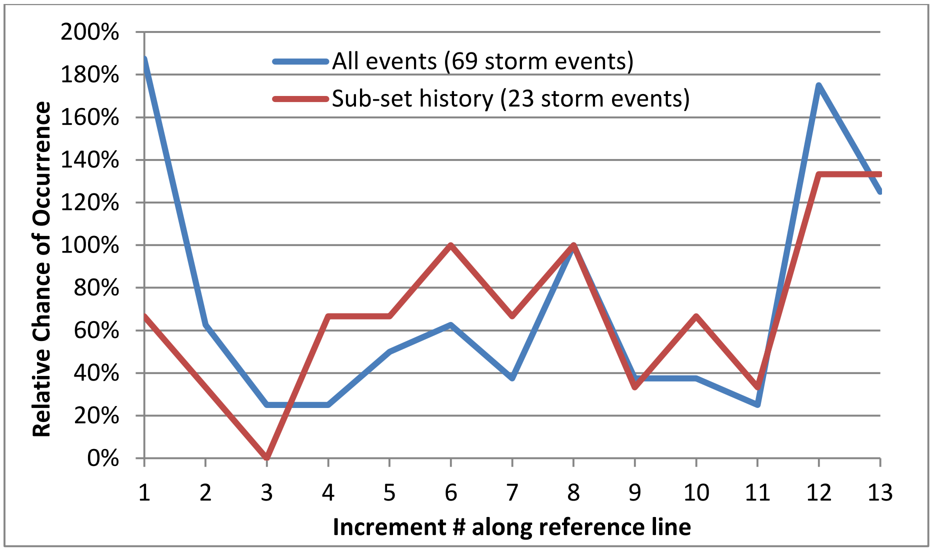

Figure 2. The Relative Chance of Storm Occurrences Along the Coast.

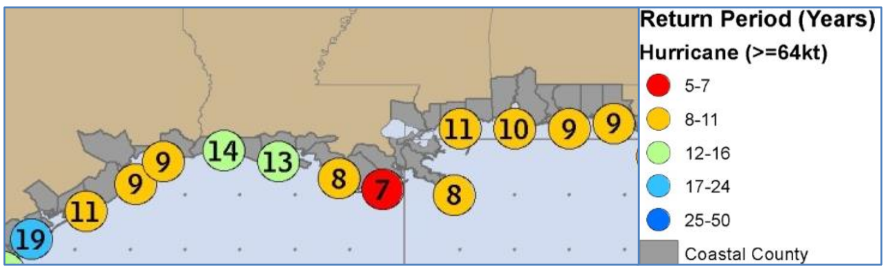

Figure 3. Historical Hurricane (1900- 2010) Distribution Along the Coast in Terms of Return Periods (http://www.nhc.noaa.gov).

3.3 Approximated History

By aligning each selected storm event with a synthetic storm, a synthetic storm approximation of the historic record was created. The details for selecting the synthetic storm representing each historical storm event are presented in Appendix D with images of historical storm track, synthetic storm track, and tables of storm dynamic parameters. In summary, Table D0 in Appendix D shows the selected storms and their matching synthetic storms with dynamic parameters. Time histories of water level, wave height, and wind speed at locations of interest (provided by CPRA and The Water Institute) were extracted per event and delivered. Note that some synthetic storms may be shorter or longer in duration than the real storms represented. One option to remedy the difference in duration between historic storm and synthetic storm analogues is to stretch the simulation results to match the actual storm duration and to avoid altering the time of landfall. Synthetic storm event data were blended into the historical record so that the corresponding temporal period in the ICM historic forcing could be removed and replaced with the results from the existing database of ADCIRC and SWAN simulations of these synthetic storms. Additional description for inserting the synthetic data into the existing time history is provided in Section 5 - Data Delivery.

In order to examine the fidelity of the approximated history using synthetic storms, the number of strikes along coastal Louisiana and the strength of storm events are reviewed and compared with that for the historical storm subset. Figure 4 shows the tracks of matching synthetic storms and the reference line, which is comparable with the plot of historical storm tracks in Figure 1.

The number of strikes within each segment of the reference line was counted and plotted in Figure 5, which indicates that selected synthetic storm tracks present a similar pattern as to the historical storms do pattern (red circles line up well with the blue crosses). There are slight discrepancies in the number of storms within some segments of the reference line. To test the sensitivity of ICM to this variation, alternative hypothetic histories were designed to explore other possibilities.

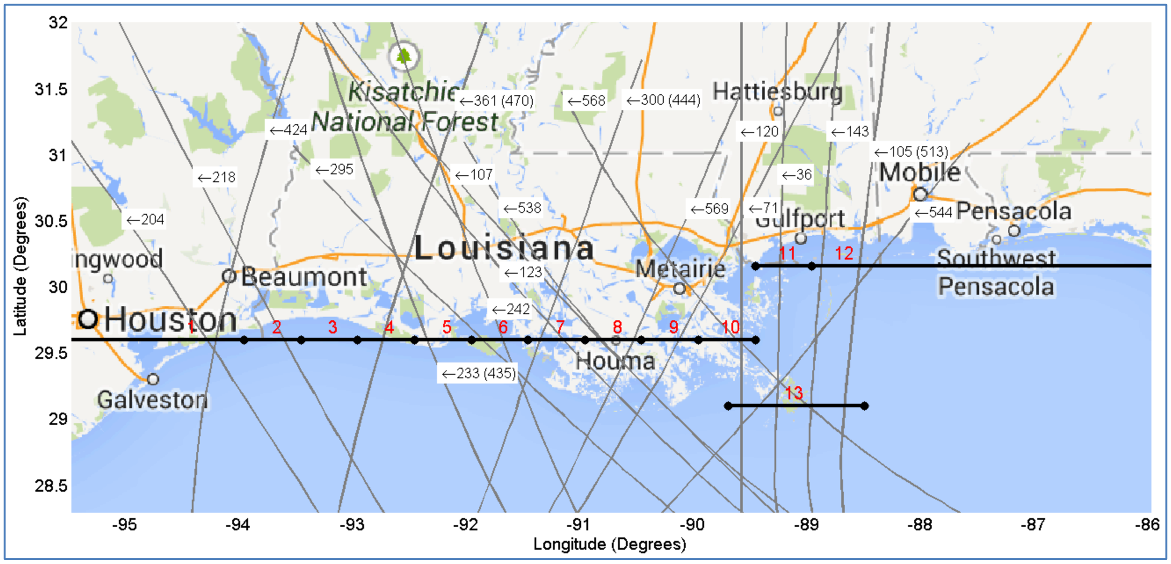

Figure 4. Synthetic Storm Tracks for Approximated History (AH1).
Note: Gray= storm tracks; black= the geographic reference line labeled with red numbers on each segment. PBL# of JPM-OS storms are labeled.

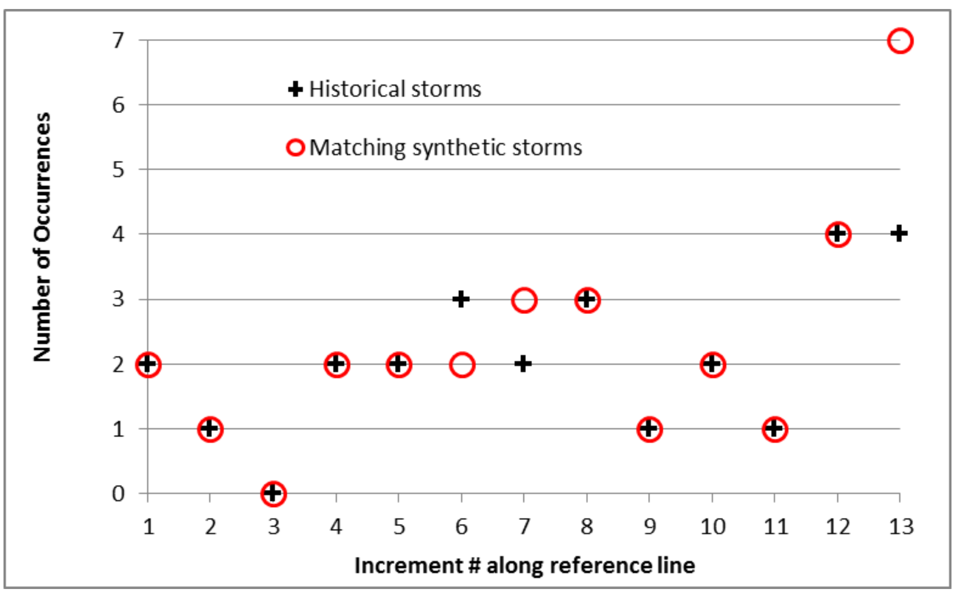

Figure 5. Number of Storm Occurrences Along the Coast.

4.0 Hypothetical Histories

The set of JPM storms used to approximate to the historical hurricanes is labeled AH1 and is described in the previous section. To test the sensitivity of the ICM to spatial and temporal variation of storm occurrence, alternative combinations of JPM storms were assembled to explore other distributions in time and space. Two spatial variations were created named AH2 (shift to the west) and AH3 (shift to the east) and one temporal variation created were named AH4. Table 2 list characteristic features of the real history, the approximated history, and the three alternatives. To express the spatial occurrence of storms east to west, the average number of storms per segment is provided separately for the west-to-central segments and for the eastern segments.

Table 2. Characteristic Features of Actual, Approximate and Alternative Histories

History ID		Storm Intensity	Storm locations	More active decades
History	N/A	60% hurricanes (45% major hurricanes) 40% tropical storms	Average per segment, up to 2 storms western/central up to 3 storms east	1950s-1960s active 1980s-1990s active 2000-2012 active
Alterative history	AH1	Hurricanes only 43% major hurricanes	Average per segment, <2 storms western to central; >2 storms eastern	2000-2012 slightly more active than other decades
Alternative history	AH2		Average per segment, 2 storms western to central <2 storms eastern	same as above
	AH3		Average per segment, 1 storm western to central; 3 storms eastern	same as above
	AH4		The same as AH1	1980s and 1990s more active than other decades

Figure 6 shows the number of occurrences in space for the various histories. The black crosses represent the actual storm occurrence. The red line represents AH1 and is the best approximation possible to the black crosses when using the JPM storm suite. The green curve represents AH2 and shows the western re-distribution of storms, while the purple curve represents AH3 and reveals the eastern re-distribution of storms relative to the red line. Additionally, note the offsetting decrease compared to AH1 to compensate for the regional increases, thus maintaining the same overall occurrence along the entire coast for AH1, AH2, and AH3. Temporal alternative AH4 makes use of the same spatial distribution as AH1.

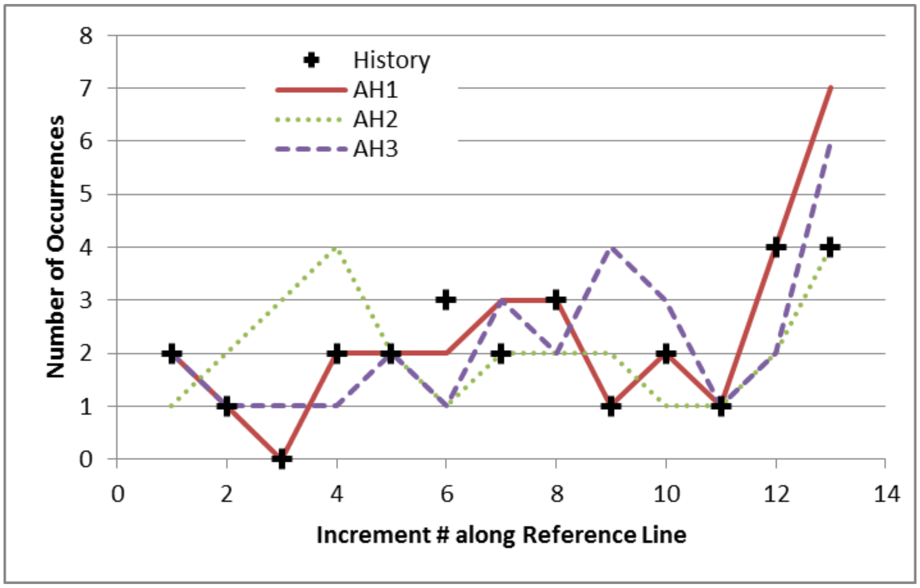

Figure 6. Number of Sorm Occurrences along the Coast for Various Alternative Histories.

The distribution of storms in time is presented in Figure 7, for which 5-year duration bins are used to organize the number of storm occurrences. Note that there are factors such as ENSO/AMO cycles that occur at time scales shorter than 5-year intervals, which impact generation and frequency of hurricanes. The effort here is not intended to explore, explain, or predict the mechanisms of storm generation. Rather than intending to show statistical trends, the 5-year bins are used simply to organize the general distribution in time and to provide a means to test the ICM sensitivity on temporal distribution of hurricanes.

Figure 7 shows that more hurricanes occurred in the late 1980s and 2000s (bars). It shows the number of occurrences in time for the alternative histories and the actual history. The blue bars indicate the total historical storms (both hurricanes and tropical storms) for each time period. The red line indicates the number of occurrences for hurricanes only (in total 41 hurricanes out of 69 storm events). The green line indicates storm occurrences for the sub-set of 23 selected storm events that are reflected by the approximated history AH1 and also for alternatives AH2 and AH3, which apply only spatial variation in storm occurrences. The yellow line represents the re-distribution in time for temporal hypothetical alternative AH4. Figures 6 and 7 provide a summary of the strategies used for creating hypothetical alternative histories.

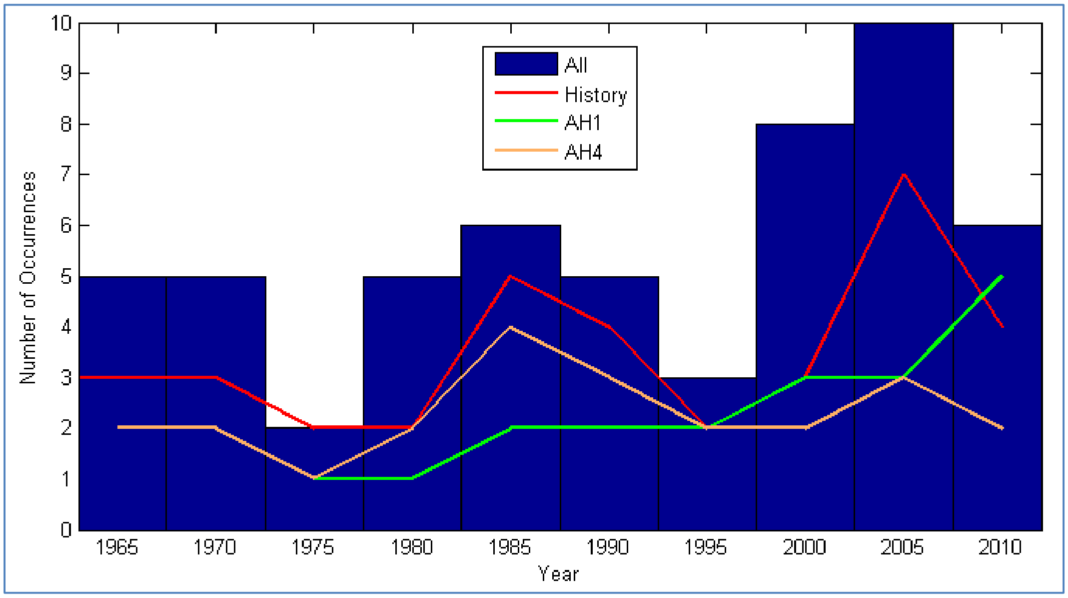

Figure 7. Number of Storm Occurrences in Time for Various Alternative Histories.
Note: Blue bars: histogram of 69 storm events; red line: 41 hurricanes out of the dataset of 69 storm events; green line: approximate history (23 storm events); yellow line: the fourth alternative hypothetic history (AH4).

4.1 AH2

A simplified schematic of JPM storms used to approximate the historical storm locations is presented in Figure 8. The x-axis shows the longitude of each storm as it crosses 29.5° latitude and the vertical axis indicates the central pressure near landfall for each indicated synthetic storm. Two spatial alternatives are constructed on the basis of the AH1 schematic shown in Figure 8 by moving some events to the west or east to increase the frequency of occurrences of storm in the west (AH2) or in the east (AH3).

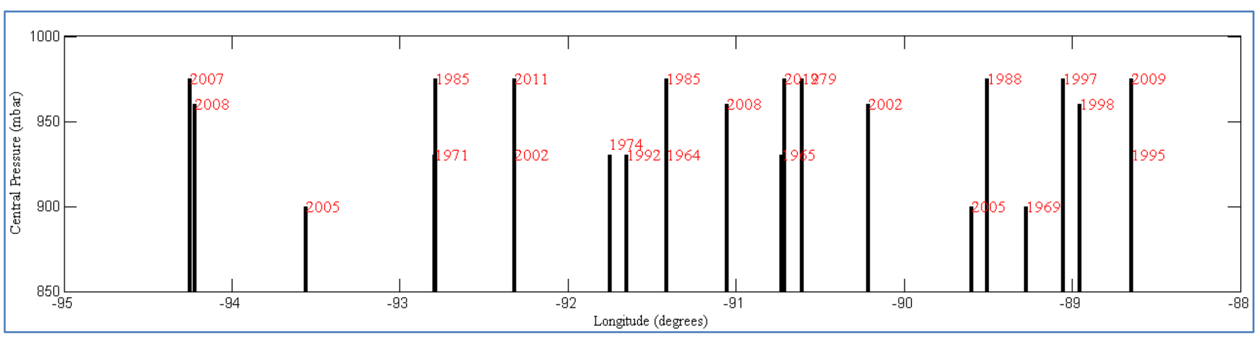

Figure 8. Spatial Distribution and Central Pressure at Landfall of JPM Synthetic Storms Intended to Match Actual Historical Events (AH1).
Note: The year of occurrence of the target event is labeled.

The relocated storms and their new JPM track and storm number are listed in Table 3 for hypothetical history AH2. The original temporal distribution is retained for AH2. Figure 9 shows the synthetic storm tracks for this history. Figure 10 shows the schematic of the storm locations and should be compared with Figure 8. Note that only 26% of storms were relocated to generate AH2, resulting in the distribution shown in Figure 6.

Table 3. Storms Moved to Create History AH2

Historical storm name	AH1		AH2		Move direction
	PBL#	Track ID	PBL#	Track ID	
Betsy	107	E2@-45	302	W2@000	Westwards
Carmen	295	W4@-45	345	W1B@-45	Westwards
Danny	470	W2B@+45	462	W1B@000	Westwards
Florence	568	E3B@-45	463	W2B@000	Westwards
Georges	143	E4B@000	341	W3B@000	Westwards
Lee	435	W4@000	471	W3B@+45	Westwards

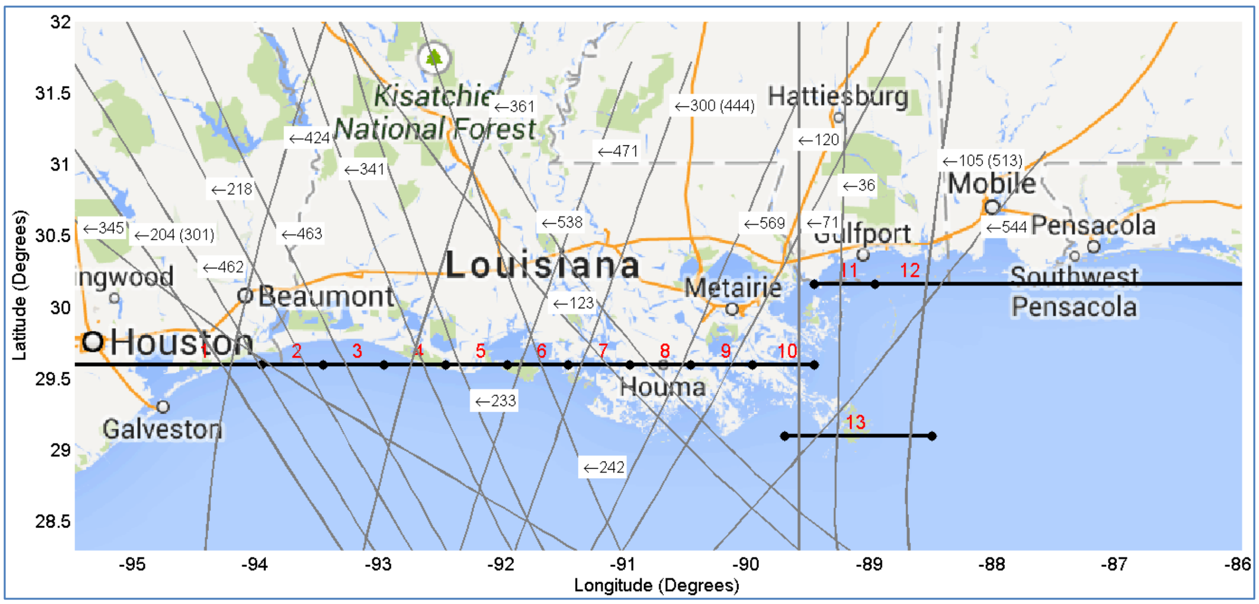

Figure 9. Selected JPM-OS Synthetic Storm Tracks for Alternate History AH2.
Note: PBL# of JPM-OS storms are labeled.

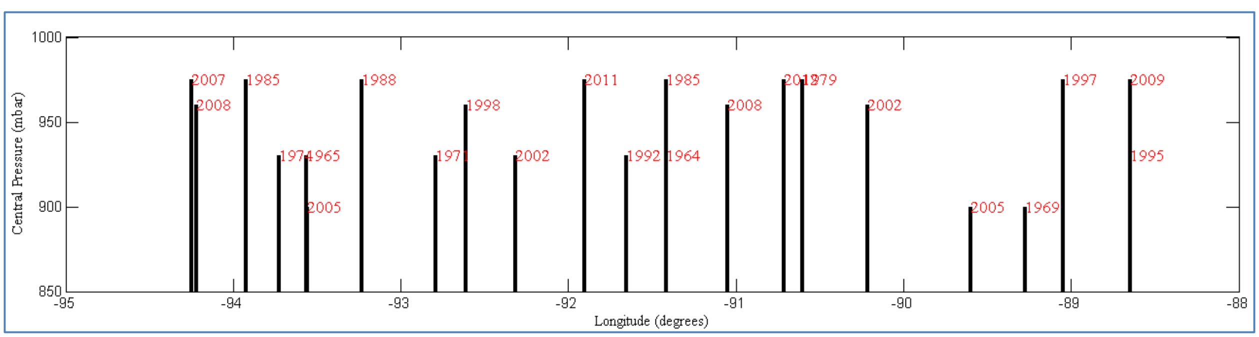

Figure 10. Spatial Distribution and Central Pressure at Landfall of JPM Synthetic Storms Selected for AH2.
Note: The year of occurrence of the target event is labeled.

4.2 AH3

This alternate history represents the possibility of more occurrences in the eastern Louisiana. Several storm events are shifted to concentrate in the eastern coastal Louisiana while slightly decreasing the frequency of storms in the west and Mississippi/Alabama coast. Similar to what was done with AH2, overall diversity in AH3 ensemble landfall location, track approaching angle, and strength of hurricanes was maintained by careful relocation of storm tracks to compensate for the imposed easterly bias. The original temporal distribution is retained for AH3. The relocated storms and their new JPM track and storm number are listed in Table 4.

Figure 11 shows the synthetic storm tracks for this history. Figure 12 shows the schematic of the storm locations and should be compared with Figure 8. Note that only 26% of storms were relocated to generate AH3, resulting in the distribution shown in Figure 6.

Table 4. Storms Moved to Create History AH3.

Historical storm name	AH1		AH3		Move direction
	PBL#	Track ID	PBL#	Track ID	
Hilda	300	W4@+45	150	E2B@+45	Eastwards
Danny	470	W2B@+45	442	W2@+45	Westwards
Andrew	242	W5@000	15	E2@000	Eastwards
Opal	105	E5@000	153	E2B@000	Westwards
Ida	513	E5@000	502	E1@000	Westwards
Isaac	538	E2@-45	539	E3@-45	Eastwards

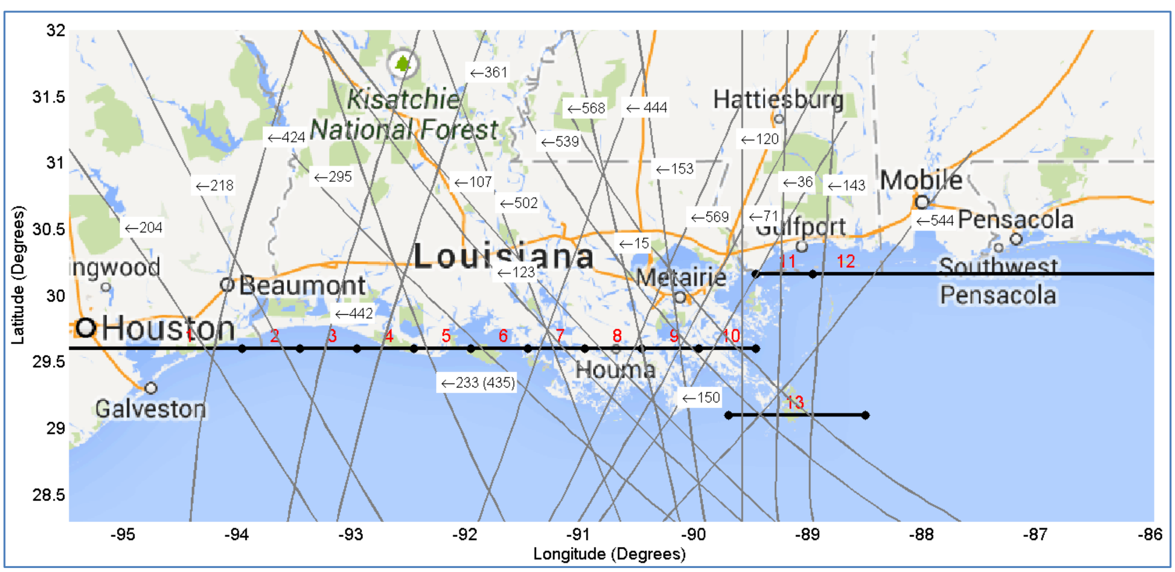

Figure 11. Selected JPM-OS Synthetic Storm Tracks for History AH3.
Note: PBL# of JPM-OS storms are labeled.

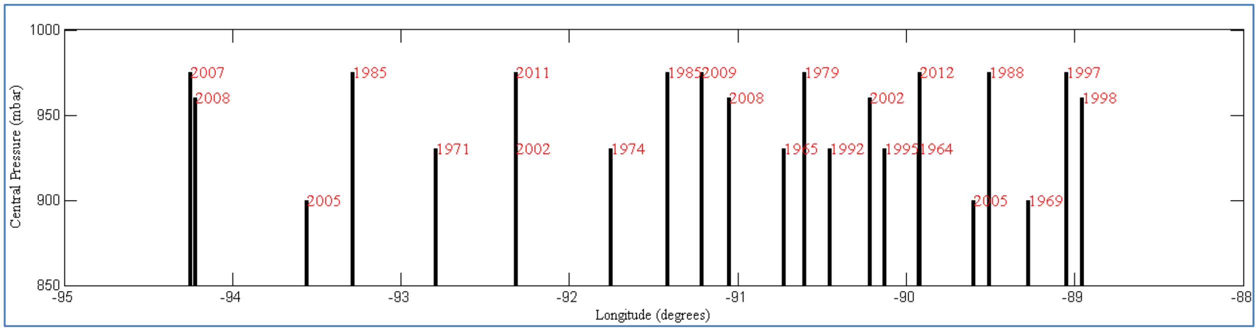

Figure 12. Spatial Distribution and Central Pressure at Landfall of JPM Synthetic Storms Selected for AH3.
Note: The year of occurrence of the target event is labeled. Note: the category is determined by the maximum wind of the synthetic storm wind field.

4.3 AH4

Figure 13 shows the best-fit JPM storms that approximate the time history of the selected 23 hurricanes over the 50-year interval of interest. The horizontal axis represents calendar year and the vertical axis indicates the central pressure near landfall of each synthetic storm that was selected for AH1. Recall that the JPM storms were selected to match the central pressure and wind speed of the historical storms between latitudes 28.5 and 31.0 as the historic storms approach the coast. The category indicated is determined by the maximum wind within that portion of history and may not represent the maximum of a storm over its entire history crossing the Gulf of Mexico. The text label indicates the historical storm event approximated by each of the synthetic storms. Note that the interval from 2000-to-present is a relatively active period with more occurrences than other intervals.

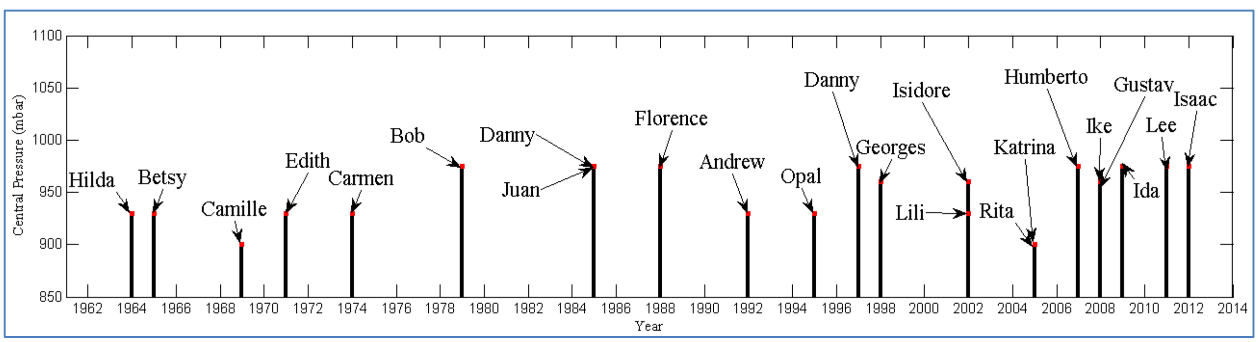

Figure 13. Calendar Year and Central Pressure at Landfall of the JPM Synthetic Storms Selected to Match a Particular Historical Event (red squares).
Note: The target historical event is labeled.

The AH4 alternative is created by reshuffling the storms in time. The storms are moved intentionally to increase the number of storm occurrences for the 1980s and 1990s. To maintain the total number of storm events, there is a compensating decrease in storm occurrences for the 21st century (see Figure 2). All storms maintain their original spatial location as in the approximate history AH1. Table 5 provides a summary of which storms were relocated and their new year of occurrence. Figure 14 provides an analog to Figure 13 for representation of the temporal re-assignment. The increased density of storms during the 1980-2000 period can be observed by comparing Figure 13 and Figure 14.

Table 5. Storms that Occur Earlier than the Actual Landfall Time in the Real History

Historical storm			
Name	Year	Year in AH1	Year in AH4
HUMBERT	2007	2007	2002
IDA	2009	2009	1984
IKE	2008	2008	1983
ISIDORE	2002	2002	1990
LILI	2002	2002	1990
RITA	2005	2005	1981

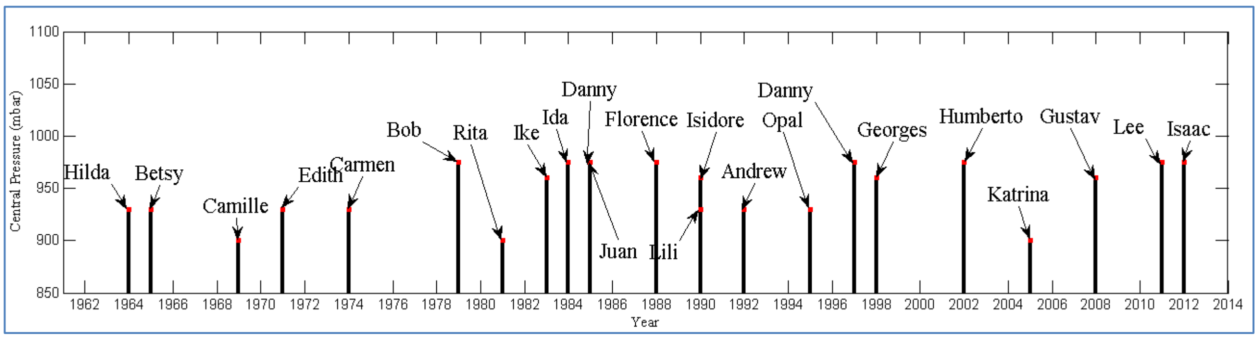

Figure 14. Calendar Year of Synthetic Storms in History AH4.
Note: The labels are the names of actual storms represented by the synthetic storms.

5.0 Data Delivery

Four storm histories were created to represent a 50-year record (1963-2012). Table 6 presents the historical storms and their synthetic storm alignments for each hypothetic alternative history. Water levels, winds, and wave heights at any location within the ADCIRC+SWAN model domain can be provided for the JPM storms in each alternative history in the format of time series or as a maximum. For instance, to re-construct the boundary condition for the ICM with different histories, time series of water levels for each event were delivered per the boundary locations provided by The Water Institute. The time sampling interval can be 15 min, 20 min, 30 min, or 1 hour. Sampling interval mainly affects the total data volume of the deliverable. When inserting the modeled time series into the existing record (tides prediction or observational records), water levels at the beginning and the end time need be smoothed in to avoid significant zigzag.

Table 6. Synthetic Storms in Approximate History and Alternative Histories.

			AH1 (AH4)		AH2		AH3	
#	**Name**	**Year**	**PBL#**	**Track ID**	**PBL#**	**Track ID**	**PBL#**	**Track ID**
1	Hilda	1964	300	W4@+45	300	W4@+45	150	E2B@+45
2	Betsy	1965	107	E2@-45	301	W1@000	107	E2@-45
3	Camille	1969	36	E4@000	36	E4@000	36	E4@000
4	Edith	1971	361	W2B@+45	361	W2B@+45	361	W2B@+45
5	Carmen	1974	295	W4@-45	345	W1B@-45	295	W4@-45
6	Bob	1979	569	E1B@+45	569	E1B@+45	569	E1B@+45
7	Danny	1985	470	W2B@+45	462	W1B@000	442	W2@+45
8	Juan	1985	444	W4@+45	444	W4@+45	444	W4@+45
9	Florence	1988	568	E3B@-45	463	W2B@000	568	E3B@-45
10	Andrew	1992	242	W5@000	242	W5@000	15	E2@000
11	Opal	1995	105	E5@000	105	E5@000	153	E2B@000
12	Danny	1997	544	E4@+45	544	E4@+45	544	E4@+45
13	Georges	1998	143	E4B@000	341	W3B@000	143	E4B@000
14	Isidore	2002	71	E2@+45	71	E2@+45	71	E2@+45
15	Lili	2002	233	W4@000	233	W4@000	233	W4@000
16	Katrina	2005	120	E3B@000	120	E3B@000	120	E3B@000
17	Rita	2005	218	W2@000	218	W2@000	218	W2@000
18	Humberto	2007	424	W1@+45	424	W1@+45	424	W1@+45

Table 6. Synthetic Storms in Approximate History and Alternative Histories.

#	Name	Year	AH1 (AH4)		AH2		AH3	
			PBL#	Track ID	PBL#	Track ID	PBL#	Track ID
19	Gustav	2008	123	E1B@-45	123	E1B@-45	123	E1B@-45
20	Ike	2008	204	W1@000	204	W1@000	204	W1@000
21	Ida	2009	513	E5@000	513	E5@000	502	E1@000
22	Lee	2011	435	W4@000	471	W3B@+45	435	W4@000
23	Isaac	2012	538	E2@-45	538	E2@-45	539	E3@-45

*Track ID name convention is seen in Appendix C
**Shaded storms are redistributed from that in AH1

Figures 15-16 are examples of time series of water surface elevation and wave height at an offshore location 40 miles to the south of barrier islands in Barataria basin. An example of point-wise cumulative rainfall estimates are presented on a map in Figure 17. A sample of the time series generated for a location in New Orleans (left of the storm track) is provided in Figure 18. The precipitation estimates can be provided to the ICM teams at any number of discrete locations across the domain and at whatever temporal resolution is required. The data format was established in coordination with the ICM teams during data delivery.

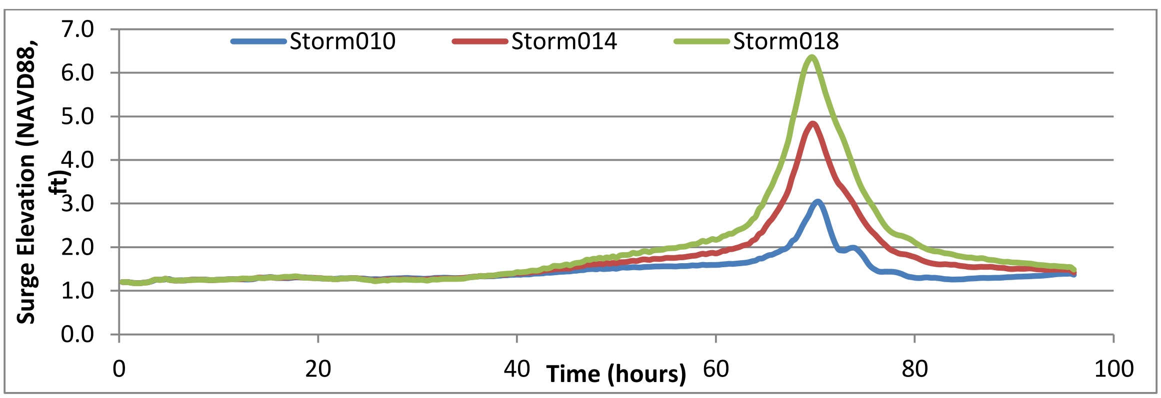

Figure 15. Water Surface Elevation (NAVD88, ft).

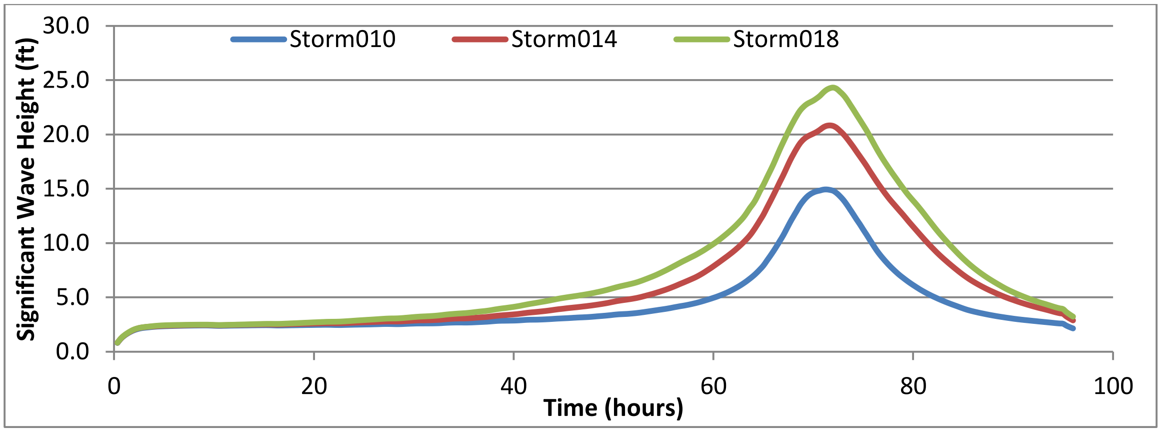

Figure 16. Significant Wave Height (ft).

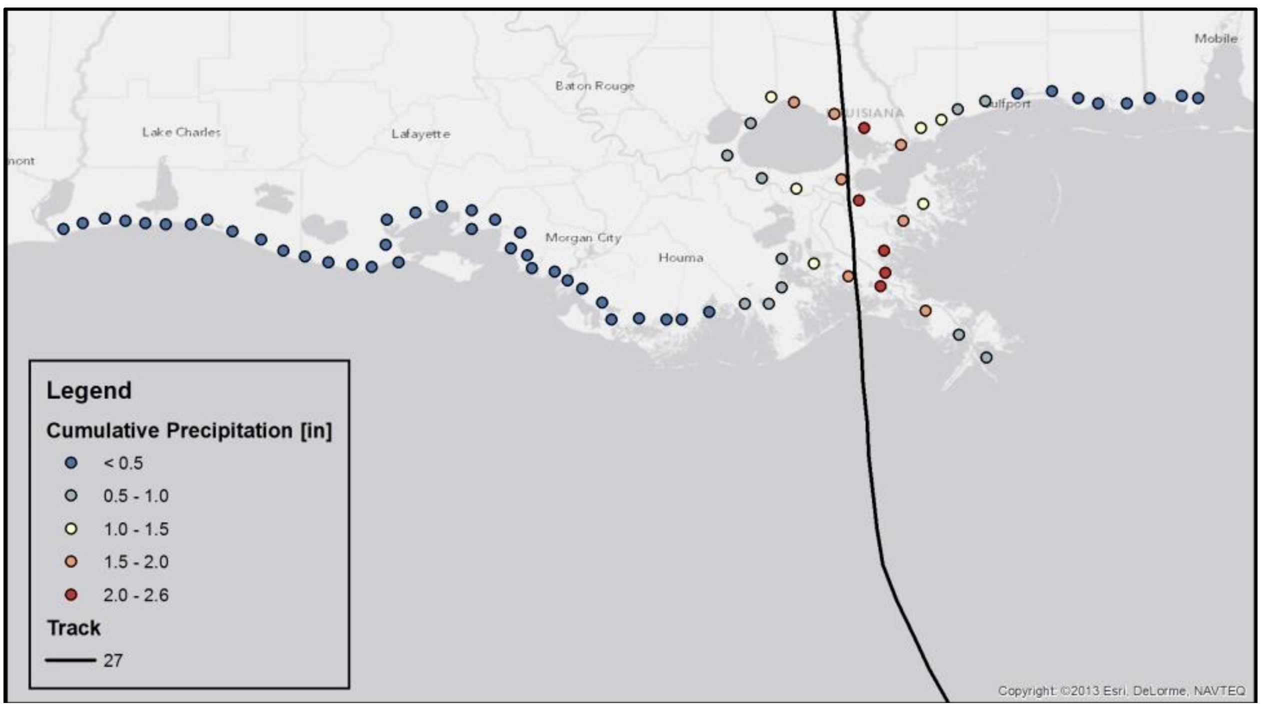

Figure 17. Cumulative Precipitation Estimates along the Louisiana Coast for Synthetic Storm 027.

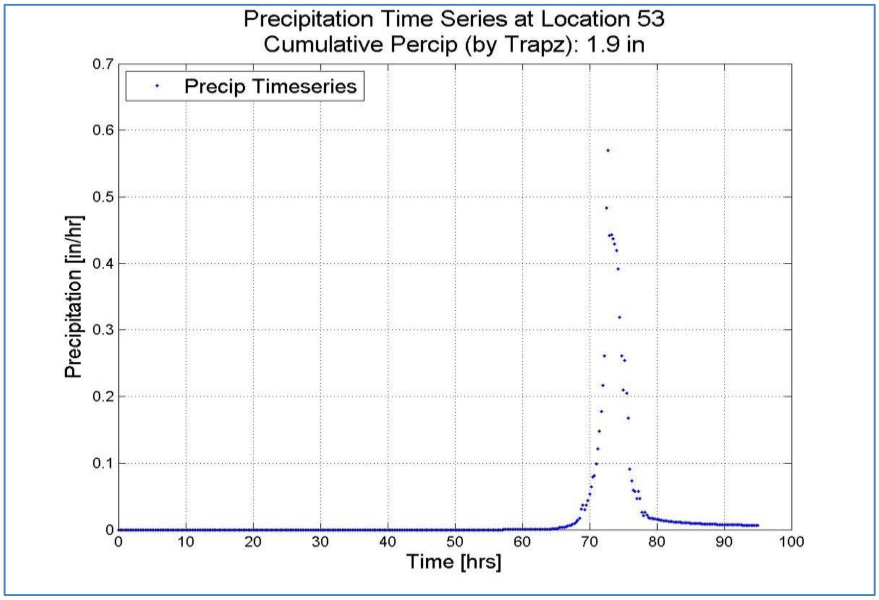

Figure 18. Time Series of Precipitation Estimates for Synthetic Storm 027 at a Location in New Orleans, Left of the Storm Track (see Figure 17).

Note: Estimates were calculated every 15 minutes for 95 hours.

6.0 Summary

- A threshold for selecting historical storms for inclusion in the ICM is recommended to be a central pressure of 982 mb which was determined by the dynamic parameters of the existing synthetic storm suite and historical storms. Due to the short range of central pressures that are considered in the JPM-OS storm suite, the capability of representing historical storms using synthetic storms is limited. More likely, only high-intensity and low-intensity hurricanes can be approximated to a certain degree. Tropical storms are not imitated using synthetic storms.
- Twenty-three hurricanes were selected and approximated by synthetic storms to form the realistic dataset of hurricane forcing. The approximated history remains the overall characteristics of spatial storm occurrences along the Louisiana coast. However it is somewhat misrepresentative for the actual storm category. This is because the JPM-OS synthetic storms were created for estimating the statistical storm surge level along the coast instead of wind forcing.
- Three hypothetical histories were created to reflect possible variation of storm occurrence in space and time in comparison to the approximated history. Alternative histories AH2 and AH3 capture the possible situations that storms could have hit the western or eastern portion of the coast more frequently than the actual history. Alternate AH4 presents the possibility of more storms making landfall in the late 20th century and fewer storms in the early 21st century. With these various storm conditions, landscape response can be explored with the ICM.
- Time series or maximum of water levels, waves, winds, and precipitation were provided at locations requested by CPRA. A brief “README” note and the electronic delivery of the data was provided separately.

7.0 References

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Appendices

Appendix A: Dimension of Storm Event

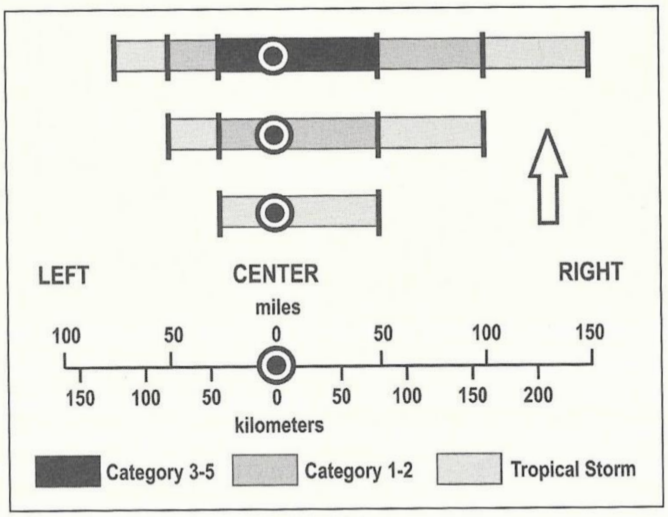
Appendix B: Historical Storm Parameters Obtained from Storm History within the 28.5-31 Degree Latitude Region

Appendix C: Synthetic Storm Parameters

Appendix D: Align Historical Storms with Synthetic Storms

Appendix A:

Figure A1. Dimension of Storm Event (Keim and Muller 2009).



Dimensions of the tropical storm and hurricane strike model used throughout the book.

Appendix B:

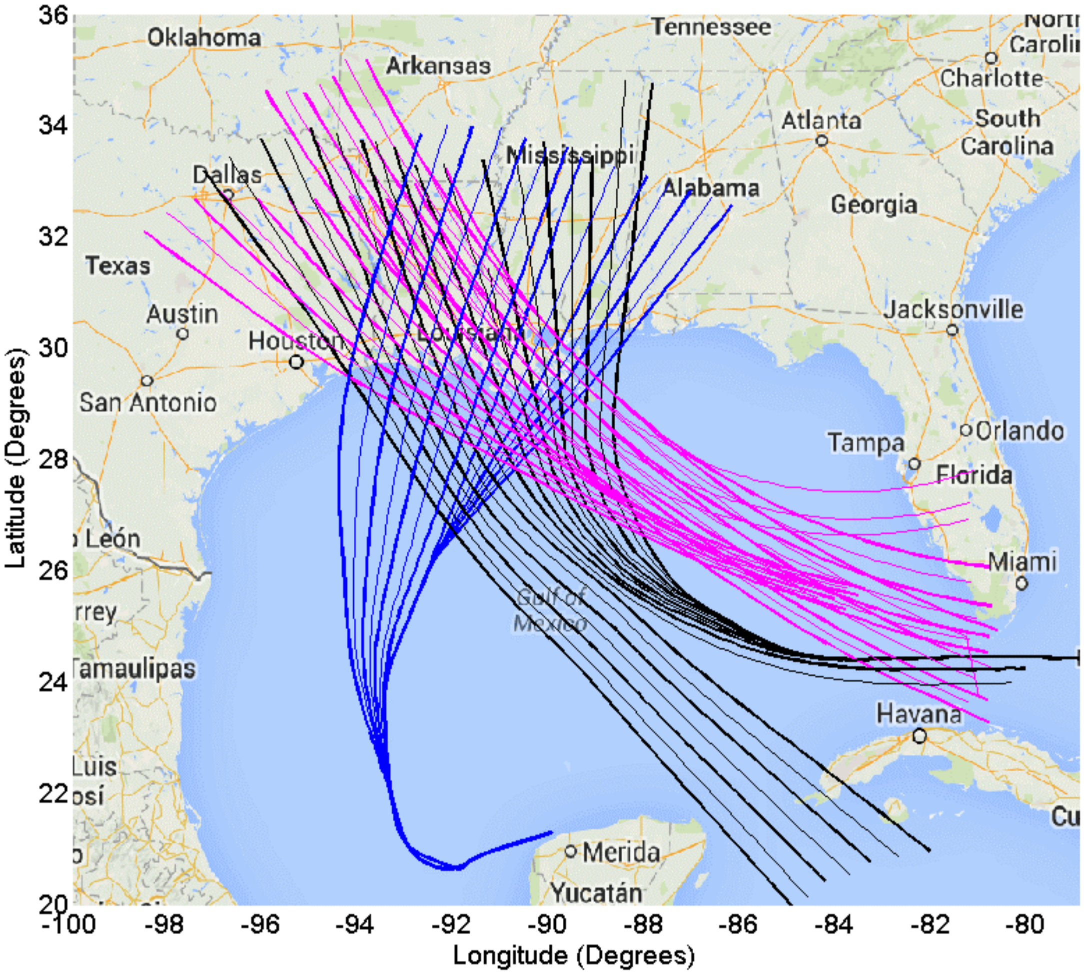
Table B1. Historical Storm Parameters Obtained from Storm History within the 28.5-31 Degree Latitude Region.

#	Name	Year	HU or TS	Minimum Cp (mbar)	Landfall Cp (mbar)	Maximum wind (knots)	Average forward speed (knots)
1	Baker	1950	HU	979	979	85	17.3
2	Barbara	1954	TS	-999	-999	40	8.2
3	Brenda	1955	TS	-999	-999	60	8.0
4	Unnamed	1955	TS	-999	-999	40	10.6
5	Unnamed	1956	TS	1004	-999	45	16.0
6	Flossy	1956	HU	980	983	80	10.4
7	Audrey	1957	HU	946	946	125	14.2
8	Bertha	1957	TS	998	-999	60	8.8
9	Esther	1957	TS	1000	1005	45	11.6
10	Arlene	1959	TS	1000	-999	50	6.8
11	Debra	1959	HU	984	984	75	4.3
12	Irene	1959	TS	1001	1001	50	9.6
13	Ethel	1960	HU	981	-999	110	8.0
14	Carla	1961	HU	931	-999	125	9.9
15	Cindy	1963	HU	996	997	70	3.6
16	Abby	1964	TS	1000	1000	55	6.8
17	Hilda	1964	HU	941	959	100	9.7
18	Betsy	1965	HU	941	948	135	16.0
19	Debbie	1965	TS	1001	-999	45	3.4
20	Camille	1969	HU	900	900	150	13.3
21	Celia	1970	HU	945	-999	70	11.0
22	Felice	1970	TS	997	997	60	14.1
23	Fern	1971	TS	978	-999	55	3.9
24	Edith	1971	HU	943	978	85	17.4
25	Carmen	1974	HU	928	-999	130	7.6
26	Babe	1977	HU	995	-999	65	6.3
27	Debra	1978	TS	1000	1000	50	10.8
28	Bob	1979	HU	986	989	65	16.9
29	Claudette	1979	TS	997	999	45	5.0
30	Frederic	1979	HU	943	955	115	12.7
31	Chris	1982	TS	994	994	55	9.0
32	Alicia	1983	HU	962	962	100	8.7
33	Danny	1985	HU	987	988	80	10.9
34	Elena	1985	HU	953	959	110	8.7
35	Juan	1985	HU	971	974	75	6.7
36	Bonnie	1986	HU	990	991	75	10.4
37	Unnamed	1987	TS	1008	1009	40	9.9
38	Beryl	1988	TS	1001	1002	45	4.7

#	Name	Year	HU or TS	Minimum Cp (mbar)	Landfall Cp (mbar)	Maximum wind (knots)	Average forward speed (knots)
39	Florence	1988	HU	982	984	70	12.2
40	Chantal	1989	HU	984	990	70	10.3
41	Jerry	1989	HU	982	987	75	12.3
42	Andrew	1992	HU	922	956	125	9.2
43	Dean	1995	TS	999	999	40	8.0
44	Opal	1995	HU	916	946	110	21.1
45	Danny	1997	HU	984	990	70	3.5
46	Earl	1998	HU	985	989	85	12.9
47	Frances	1998	TS	990	990	55	7.9
48	Georges	1998	HU	961	965	95	4.5
49	Hermine	1998	TS	999	1002	40	5.8
50	Allison	2001	TS	1002	1004	50	8.3
51	Hanna	2002	TS	1001	1002	50	11.1
52	Isidore	2002	TS	960	985	55	14.3
53	Lili	2002	HU	938	970	105	13.3
54	Bill	2003	TS	997	997	50	13.3
55	Claudette	2003	HU	979	-999	80	12.3
56	Grace	2003	TS	1007	1007	35	12.5
57	Ivan	2004	HU	910	946	115	12.2
58	Matthew	2004	TS	997	1000	40	12.3
59	Cindy	2005	HU	991	994	65	12.3
60	Dennis	2005	HU	930	958	120	16.0
61	Katrina	2005	HU	902	920	125	14.7
62	Rita	2005	HU	895	943	105	10.8
63	Humberto	2007	HU	985	987	80	8.8
64	Edouard	2008	TS	996	998	55	10.2
65	Gustav	2008	HU	954	956	95	12.9
66	Ike	2008	HU	944	955	95	12.3
67	Ida	2009	HU	975	998	75	8.1
68	Lee	2011	TS	986	987	50	5.1
69	Isaac	2012	HU	965	967	70	5.6

Appendix C: Synthetic Storm Parameters

Figure C1. Synthetic Storm Tracks in the JPM-OS Storm Suite



Thick lines: primary tracks from west to east

- Zero approaching angle: W1, W2, W3, W4, W5, E1, E2, E3, E4, and E5;
- Negative 45° azimuth: W1@-45, W2@-45, W3@-45, W4@-45, E1@-45, E2@-45, E3@-45, and E4@-45;
- Positive 45° azimuth: W1@+45, W2@+45, W3@+45, W4@+45, E1@+45, E2@+45, E3@+45, and E4@+45;

Thin lines: secondary tracks from west to east

- Zero approaching angle: W1B, W2B, W3B, W4B, E1B, E2B, E3B, and E4B;
- Negative 45° azimuth: W1B@-45, W2B@-45, W3B@-45, E1B@-45, E2B@-45, and E3B@-45;
- Positive 45° azimuth: W1B@+45, W2B@+45, W3B@+45, E1B@+45, E2B@+45, and E3B@+45;

Table C1. Synthetic Storm Tracks and Dynamic Parameters

Storm track ID	Synthetic storms (JPM-OS storm number)	Cp (mbar)	Forward speed (knots)	Radius of maximum wind (nm)
E1@000	1, 2, 3, 4, 5, 6, 7, 8, 9, 82, 83, 101, 501, 502, 503, 532, 545	900, 930, 960, 975	6, 11, 17	6.0, 8.0, 11.0, 14.9, 17.7, 21.0, 21.8, 25.8, 35.6
E2@000	10, 11, 12, 13, 14, 15, 16, 17, 18, 84, 85, 102, 504, 505, 506, 533, 546			
E3@000	19, 20, 21, 22, 23, 24, 25, 26, 27, 86, 87, 103, 507, 508, 509, 534, 547			
E4@000	28, 29, 30, 31, 32, 33, 34, 35, 36, 88, 89, 104, 510, 511, 512, 535, 548			
E5@000	37, 38, 39, 40, 41, 42, 43, 44, 45, 90, 91, 105, 513, 514, 515, 536, 549			
E1@-45, Vf=17 or 6, 11	46, 47, 48, 49, 92, 516, 517, 537	900, 930, 960, 975	6, 11	12.5, 18.2, 18.4, 24.6
	106, 550	930, 975	17	17.7
E2@-45, Vf=17 or 6, 11	50, 51, 52, 53, 93, 518, 519, 538	900, 930, 960, 975	6, 11	12.5, 18.2, 18.4, 24.6
	107, 551	930, 975	17	17.7
E3@-45, Vf=17 or 6, 11	54, 55, 56, 57, 94, 520, 521, 539	900, 930, 960, 975	6, 11	12.5, 18.2, 18.4, 24.6
	108, 552	930, 975	17	17.7
E4@-45, Vf=17 or 6, 11	58, 59, 60, 61, 95, 522, 523, 540	900, 930, 960, 975	6, 11	12.5, 18.2, 18.4, 24.6
	109, 553	930, 975	17	17.7
E1@+45	66, 67, 68, 69, 97, 111, 524, 525, 541, 554	900, 930, 960, 975	6, 11, 17	12.5, 17.7, 18.2, 18.4, 24.6
E2@+45	70, 71, 72, 73, 98, 112, 526, 527, 542, 555			
E3@+45	74, 75, 76, 77, 99, 113, 528, 529, 543, 556			
E4@+45	78, 79, 80, 81, 100, 114, 530, 531, 544, 557			
E1B@000, Vf=6 or 11, 17	115, 116, 152, 558	900, 930, 960, 975	11, 17	17.7
	137, 138, 562	900, 960, 975	6	
E2B@000	117, 118, 139, 140, 153, 559, 563	900, 930, 960, 975	6, 11, 17	
E3B@000	119, 120, 141, 142, 154, 560, 564			
E4B@000	121, 122, 143, 144, 155, 561, 565			
E1B@-45, Vf=6, 11, or 17	123, 126	900, 960	11	17.7
	145, 566	930, 975	6	17.7
	156	930	17	17.7
E2B@-45, Vf=6, 11, or 17	124, 127	900, 960	11	17.7
	146, 567	930, 975	6	17.7
	157	930	17	17.7
E3B@-45, Vf=6, 11, or 17	125, 128	900, 960	11	17.7
	147, 568	930, 975	6	17.7
	158	930	17	17.7
E1B@+45	131, 132, 149, 160, 569	900, 930, 960, 975	6, 11, 17	17.7
E2B@+45	133, 134, 150, 161, 570			
E3B@+45	135, 136, 151, 162, 571			
W1@000	201, 202, 203, 204, 205, 206, 207, 208, 209, 282, 283, 301, 401, 402, 403, 432, 445	900, 930, 960, 975	6, 11, 17	6.0, 8.0, 11.0, 14.9, 17.7, 21.0, 21.8, 25.8, 35.6
W2@000	210, 211, 212, 213, 214, 215, 216, 217, 218, 284, 285, 302, 404, 405, 406, 433, 446			
W3@000	219, 220, 221, 222, 223, 224, 225, 226, 227, 286, 287, 303, 407, 408, 409, 434, 447			

Table C1. Synthetic Storm Tracks and Dynamic Parameters

Storm track ID	Synthetic storms (JPM-OS storm number)	Cp (mbar)	Forward speed (knots)	Radius of maximum wind (nm)
W4@000	228, 229, 230, 231, 232, 233, 234, 235, 236, 288, 289, 304, 410, 411, 412, 435, 448			
W5@000	237, 238, 239, 240, 241, 242, 243, 244, 245, 290, 291, 305, 413, 414, 415, 436, 449			
W1@-45	246, 247, 248, 249, 292, 306, 416, 417, 437, 450	900, 930, 960, 975	6, 11, 17	12.5, 17.7, 18.2, 18.4, 24.6
W2@-45	250, 251, 252, 253, 293, 307, 418, 419, 438, 451			
W3@-45	254, 255, 256, 257, 294, 307, 418, 419, 439, 452			
W4@-45	258, 259, 260, 261, 295, 307, 418, 419, 440, 453			
W1@+45	266, 267, 268, 269, 297, 311, 424, 425, 441, 454			
W2@+45	270, 271, 272, 273, 298, 312, 426, 427, 442, 455			
W3@+45	274, 275, 276, 277, 299, 313, 428, 429, 443, 456			
W4@+45	278, 279, 280, 281, 300, 314, 430, 431, 444, 457			
W1B@000	315, 316, 337, 338, 352, 458, 462	900, 930, 960, 975	6, 11, 17	17.7
W2B@000	317, 318, 339, 340, 353, 459, 463			
W3B@000	319, 320, 341, 342, 354, 460, 464			
W4B@000	321, 322, 343, 344, 355, 461, 465			
W1B@-45	323, 326, 345, 356, 466	900, 930, 960, 975	6, 11, 17	17.7
W2B@-45	324, 327, 346, 357, 467			
W3B@-45	325, 328, 347, 358, 468			
W1B@+45	331, 332, 349, 360, 469			
W2B@+45	333, 334, 350, 361, 470			
W3B@+45	335, 336, 351, 362, 471			

Appendix D: Align Historical Storms with Synthetic Storms

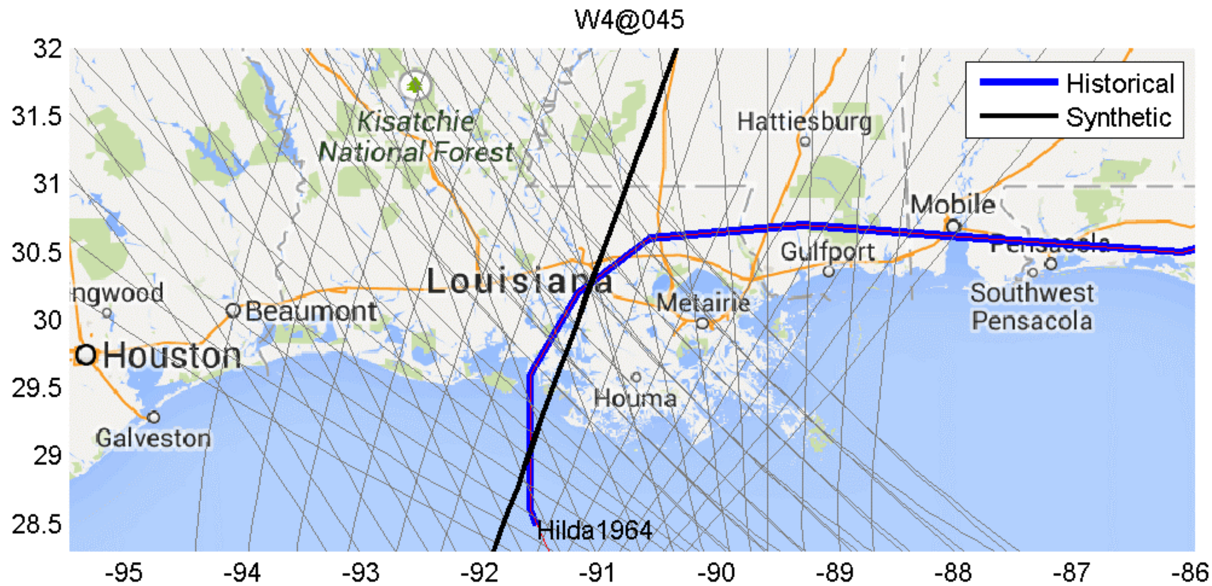
The following pages include rationale of how a matching synthetic storm is selected. The image for each storm event illustrates the historic track and a matching synthetic storm track (as titled) selected from the synthetic storm suite (gray lines). The synthetic track ID is denoted as, for instance, W4@-045, which means a fourth primary track that is of an angle of negative 45 degrees from the true north and makes landfall in the western parishes of Louisiana. The letter "B", if exists before the sign of "@", means it is a secondary track that lies in between two primary tracks. For instance, E2B@000 lies between E2@000 and E3@00. For all the track IDs of all tracks in the JPM-OS storm suite, please refer to Appendix C.

*Table D1. Selected Storms and Matching Synthetic Storms**

#	Name	Year	Cp (mb)	Vf (kt)	Maximum wind speed (knots)	AH1 (AH4)		Cp (mb)	Vf (kt)	Maximum wind speed (knots)
						PBL#	Track ID			
1	Hilda	1964	941	10	100	300	W4@+45	930	6	109
2	Betsy	1965	941	16	135	107	E2@-45	930	17	108
3	Camille	1969	900	13	150	36	E4@000	900	11	112
4	Edith	1971	943	17	85	361	W2B@+45	930	17	108
5	Carmen	1974	937	8	130	295	W4@-45	930	6	94
6	Bob	1979	986	17	65	569	E1B@+45	975	6	67
7	Danny	1985	987	11	80	470	W2B@+45	975	6	67
8	Juan	1985	971	7	75	444	W4@+45	975	6	67
9	Florence	1988	982	12	70	568	E3B@-45	975	6	67
10	Andrew	1992	937	9	125	242	W5@000	930	11	100
11	Opal	1995	916	21	110	105	E5@000	930	17	109
12	Danny	1997	984	3	70	544	E4@+45	975	6	67
13	Georges	1998	961	4	95	143	E4B@000	960	6	78
14	Isidore	2002	960	14	55	71	E2@+45	960	11	82
15	Lili	2002	938	13	105	233	W4@000	930	11	100
16	Katrina	2005	913	15	125	120	E3B@000	900	11	113
17	Rita	2005	895	11	105	218	W2@000	900	11	111
18	Humberto	2007	985	9	80	424	W1@+45	975	11	75
19	Gustav	2008	954	13	95	123	E1B@-45	960	11	85
20	Ike	2008	944	12	95	204	W1@000	960	11	100
21	Ida	2009	975	8	75	513	E5@000	975	11	77
22	Lee	2011	986	5	50	435	W4@000	975	6	68
23	Isaac	2012	965	6	70	538	E2@-45	975	6	67

* parameters are obtained for storm history within the 28.5-31 degree latitude region.

Figure D1. October 2-3, 1964 (Hilda)

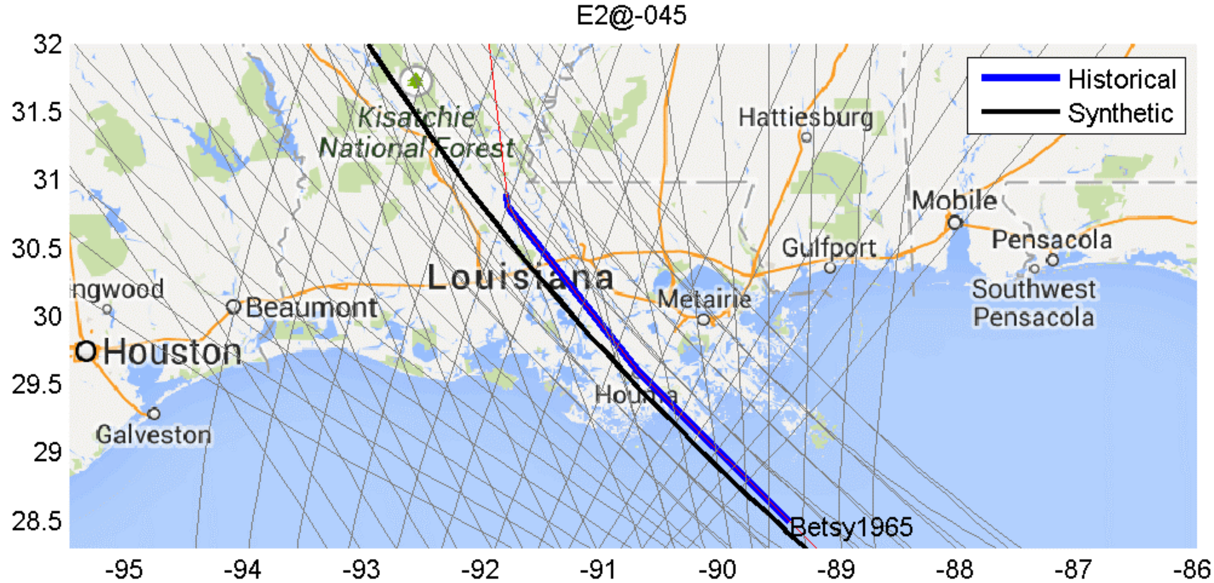


Hurricane Hilda made landfall in the Atchafalaya Basin and moved toward the east for the rest of its life. There is no similar synthetic storm track for its entire life. Only the part before its turn can be matched with track W4@+45. Among all the synthetic storms that follow this track, Storm 300 is the one with the closest central pressure and forward speed. However large discrepancies exist. Storm 278 might be a secondary choice with Cp = 960 mbar and Vf = 11 knots.

Table D2. Hurricane Hilda Dynamic Parameters.

HILDA (1964)	Category	Offshore Cp (mbar)	Forward speed (knots)	Maximum wind speed (knots)	Size (nm)	Landfall time
History	H3	941	10	100	NA	4-Oct-1964 0000
Storm 300	H3	930	6	109	17.7	28-Jul-2105 01:00:00 + 96.0hrs

Figure D2. September 9-10, 1965 (Betsy).

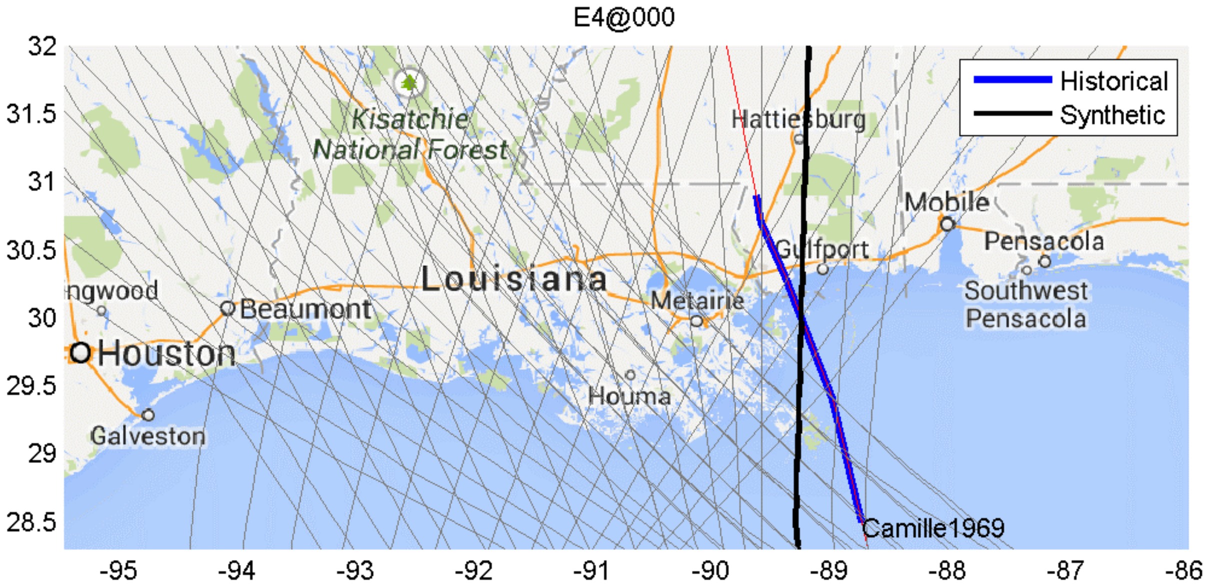


Hurricane Betsy made landfall at Grand Isle as a major hurricane. Its track matches well with the second synthetic primary track with an angle of minus 45 degrees (turn toward west) as shown in the image above. E2@-045 was selected as a best matching track. Among all the synthetic storms that follow this track, Storm 107 is the one with the closest central pressure and forward speed. Discrepancies are noticed in Table D3.

Table D3. Hurring Betsy Dynamic Parameters.

BETSY (1965)	Category	Offshore Cp (mbar)	Forward speed (knots)	Maximum wind speed (knots)	Size (nm)	Landfall time
History	H4-5	941	16	135	NA	10-Sep-1965 0600
Storm 107	H3	930	17	108	17.7	30-Jul-2112 12:00:00 + 36.0hrs

Figure D3. August 17-18, 1969 (Camille).

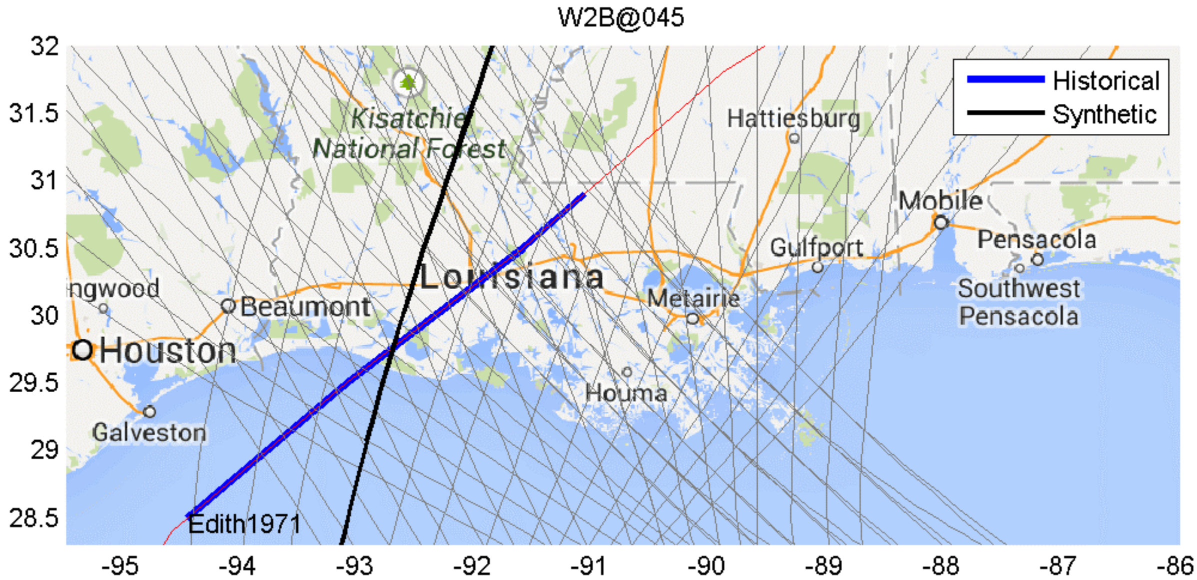


Hurricane Camille made landfall at Waveland, MS. No synthetic storm track can match the approaching angle of Hurricane Camille. The most approximate one is the fourth primary track with an angle of zero degrees (E4@000), which deviates somewhat from the historical storm track to the west in the offshore and to the west in the inland areas. This inconsistency results in the discrepancies in wind direction in the areas between the synthetic track and the historical track. Note that there are no JPM storms with wind speeds as high as those measured during Camille.

Table D4. Hurricane Camille Dynamic Parameters.

CAMILLE (1969)	Category	Offshore Cp (mbar)	Forward speed (knots)	Maximum wind speed (knots)	Size (nm)	Landfall time
History	H4-5	900	13	150	NA	18-Aug-1969 0400
Storm 036	H-3	900	11	112	21.8	29-Jul-2041 01:00:00 + 71.0hrs

Figure D4. September 5-16, 1971: (Edith).

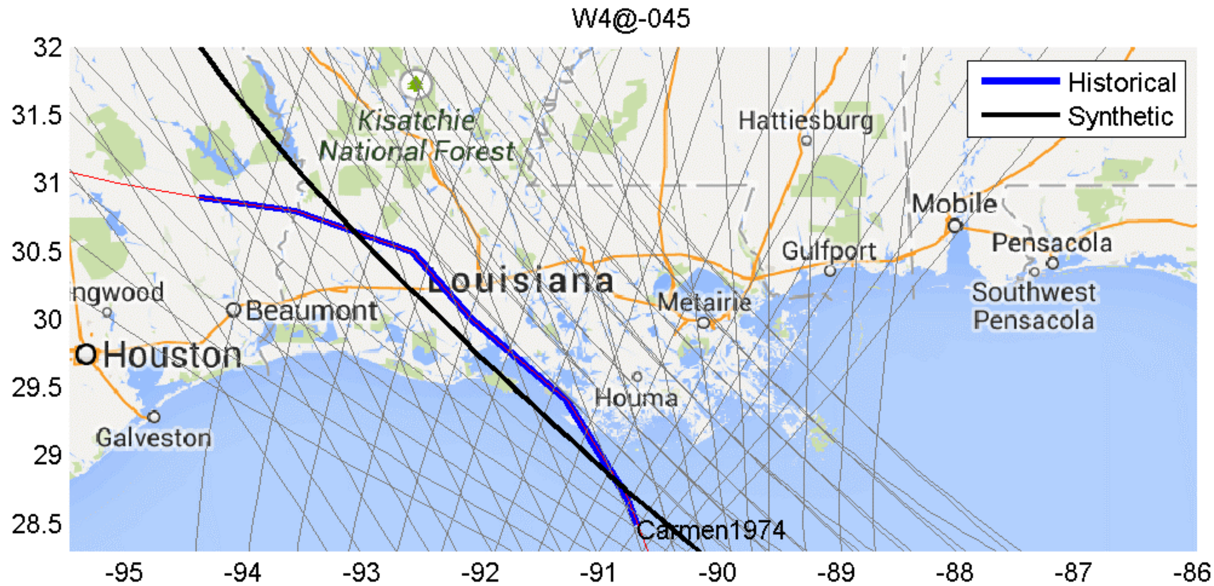


Hurricane Edith made landfall on Louisiana with winds of 80 knots on September 16. It moved toward northeast with a forward speed of 17.4 knots when it approached to the shoreline. The heaviest rains were concentrated along and just left of its track across the Atchafalaya swamp, with the maximum amount reported at Lake Arthur, where 8.29" was measured. No synthetic storm track can match the approaching angle of Hurricane Edith. Track W2B@+45 is the best match for the landfall location.

Table D5. Hurricane Edith Dynamic Parameters.

EDITH (1971)	Category	Offshore Cp (mbar)	Forward speed (knots)	Maximum wind speed (knots)	Size (nm)	Landfall time
History	H2	943	17	85	NA	16-Sep-1971 1200
Storm 361	H3	930	17	108	17.7	29-Jul-2006 20:00:00 + 51.5hrs

Figure D5. September 7-8th, 1974 (Carmen).

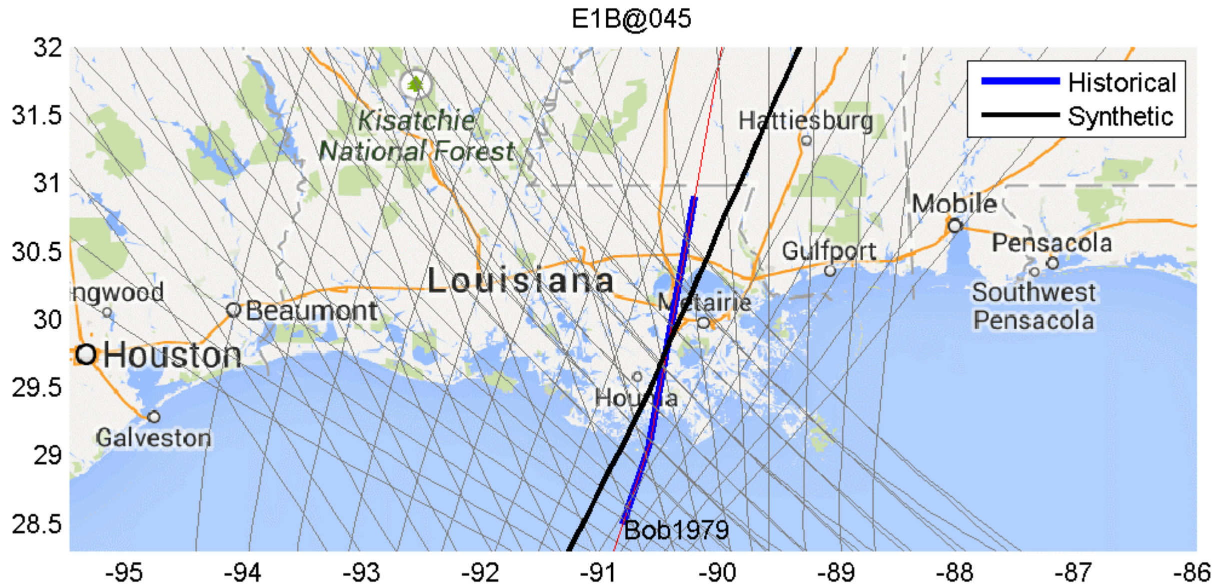


Carmen moved inland just east of Vermilion Bay near Point Au Fer after crossing the Gulf of Mexico as a major hurricane with 15 foot seas at the coast. The synthetic storm track of W4@-45 matches the real storm track well.

Table D6. Hurricane Carmer Dynamic Parameters.

CARMEN (1974)	Category	Offshore Cp (mbar)	Forward speed (knots)	Maximum wind speed (knots)	Size (nm)	Landfall time
History	H4-5	937	8	130	NA	8-Sep-1974 0600
Storm 295	H2	930	6	94	17.7	28-Jul-2100 17:00:00 + 85.0hrs

Figure D6. July 11, 1979 (Bob).

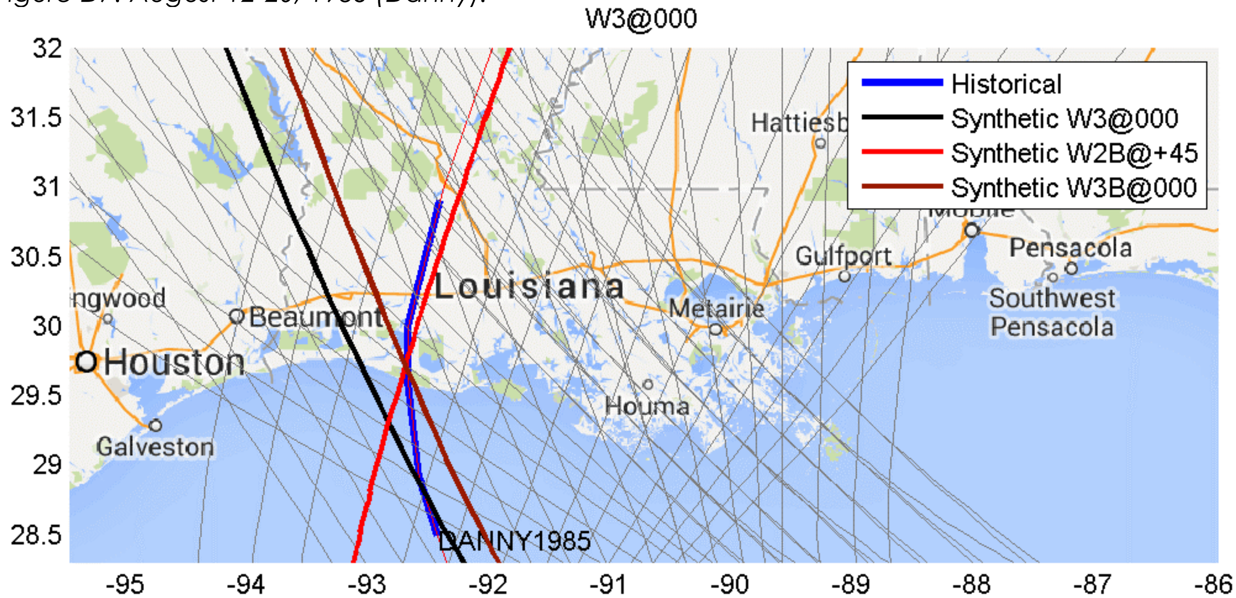


Hurricane Bob struck Terrebonne bay on the 11th. Highest storm surge reported was 5.02 ft on the north end of the causeway bridge across Lake Pontchartrain. Heavy rains fell mainly east of the Atchafalaya Swamp, with a maximum of 7.16" recorded Springville Fire Tower. The synthetic storm track of E1B@+45 is most representative. Among the storms that follow this track, Storm 569 is selected as the analog of the historical event. It is noticed that within the secondary tracks (denoted as "B") no low intensity storms move with the forward speed of 17 knots. Therefore there is a big offset in the forward speed between historical storm and its analog of synthetic storm.

Table D7. Hurricane Bob Dynamic Parameters.

BOB (1979)	Category	Offshore Cp (mbar)	Forward speed (knots)	Maximum wind speed (knots)	Size (nm)	Landfall time
History	H1	986	17	65	NA	11-Jul-1979 1200
Storm 569	H1	975	6	67	17.7	28-Jul-2006 01:00:00 + 93.5 hrs

Figure D7. August 12-20, 1985 (Danny).

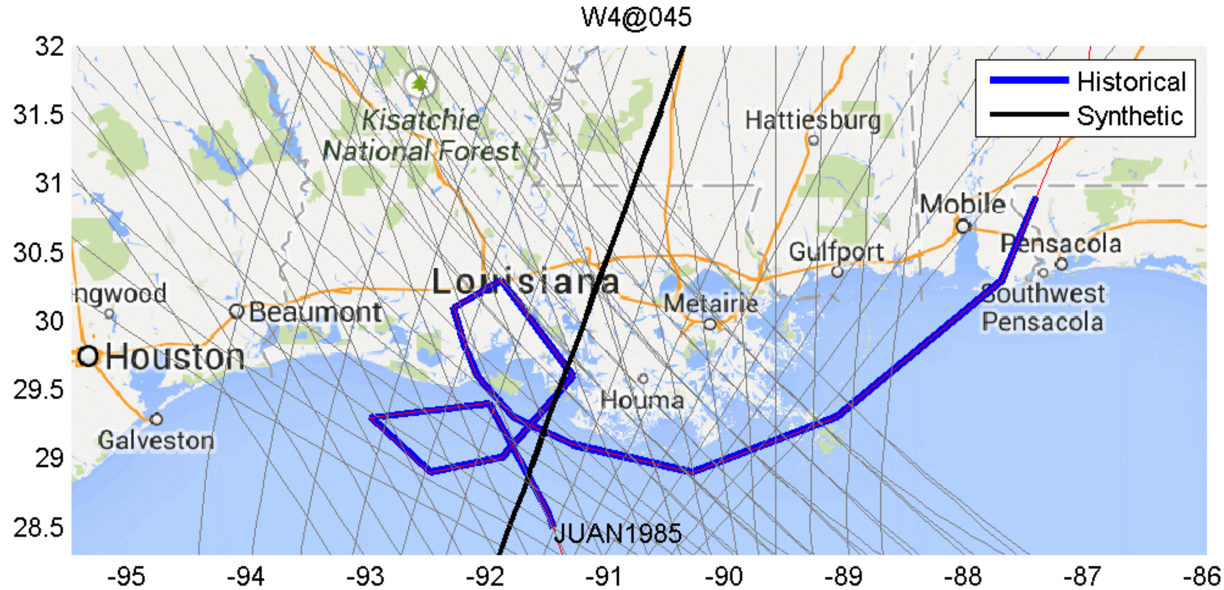


Hurricane Danny made landfall near Grand Chenier, Louisiana at its peak intensity with winds of 80 knots. There are four synthetic storm tracks that show similarity with the historical one. The track W2B@+45 follows the direction that the historical storm moved after it made landfall. Tracks W3@000 and W3B@000 follow the direction that the historical storm moved before it made landfall and W3B@000 makes landfall at the same location as the historical storm did. The W2B@+45 track is a good track to match inland winds, while track W3@000 is a good match for the offshore storm and track W3B@000 is a good match to the landfall location. Storm 408 follows the track of W3@000 that aligns with the actual track before the storm made landfall. Storm 460 follows the track of W3B@000 that matches the historical landfall location. Storm 470 follows the track of W2B@+45 that aligns the best with the historical track after it made landfall. Storm 408 is recommended because it closely follows the historical track before the storm made landfall, which ensembles the wind fields and the forward speed better. All three storms are listed in the table for reference.

Table D8. Hurricane Danny Dynamic Parameters.

DANNY (1985)	Category	Offshore Cp (mbar)	Forward speed (knots)	Maximum wind speed (knots)	Size (nm)	Landfall time
History	H1	987	11	80	NA	15-Aug-1985 1630
Storm 408	H1	975	11	75	21.0	29-Jul-2025 02:00:00 + 69.5hrs
Storm 470	H1	975	6	67	17.7	28-Jul-2006 01:00:00 + 93.5hrs
Storm 460	H1	975	11	75	17.7	29-Jul-2124 02:00:00 + 65.0 hrs

Figure D8. October 27-31, 1985 (Juan).

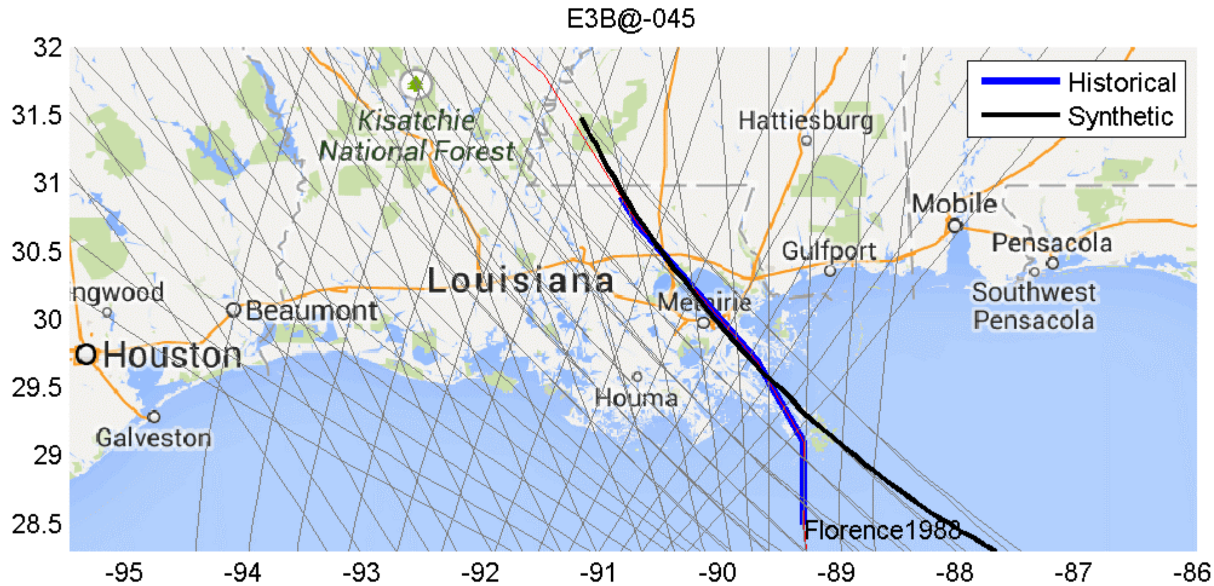


This large storm drifted northward, looping near southern Louisiana between the 28th and the 30th while weakening back into a tropical storm. Over ten inches of rain fell across Imperial Calcasieu as well as portions of southeastern Louisiana, with Galliano receiving 17.78". Storm surges reached eight feet at Cocodrie. Highway LA 1 south of Leeville and Highway LA 3090 near Fourchon were destroyed. Three bridges were washed out near Lacombe on LA 434. While it caused serious flooding and rainfall damage, unfortunately there is no match of a synthetic storm simply due to the loops of the real track. In order to capture some of its effects, Storm 444 is selected, which moves relatively slow and follows the track of W4@+45 representing the general moving direction of Juan.

Table D9. Hurricane Juan Dynamic Parameters.

JUAN (1985)	Category	Offshore Cp (mbar)	Forward speed (knots)	Maximum wind speed (knots)	Size (nm)	Landfall time
History	H1	971	7	75	NA	29-Oct-1985 1100
Storm 444	H1	975	6	67	17.7	28-Jul-2105 01:00:00 + 96.0hrs

Figure D9. September 9, 1988 (Florence).

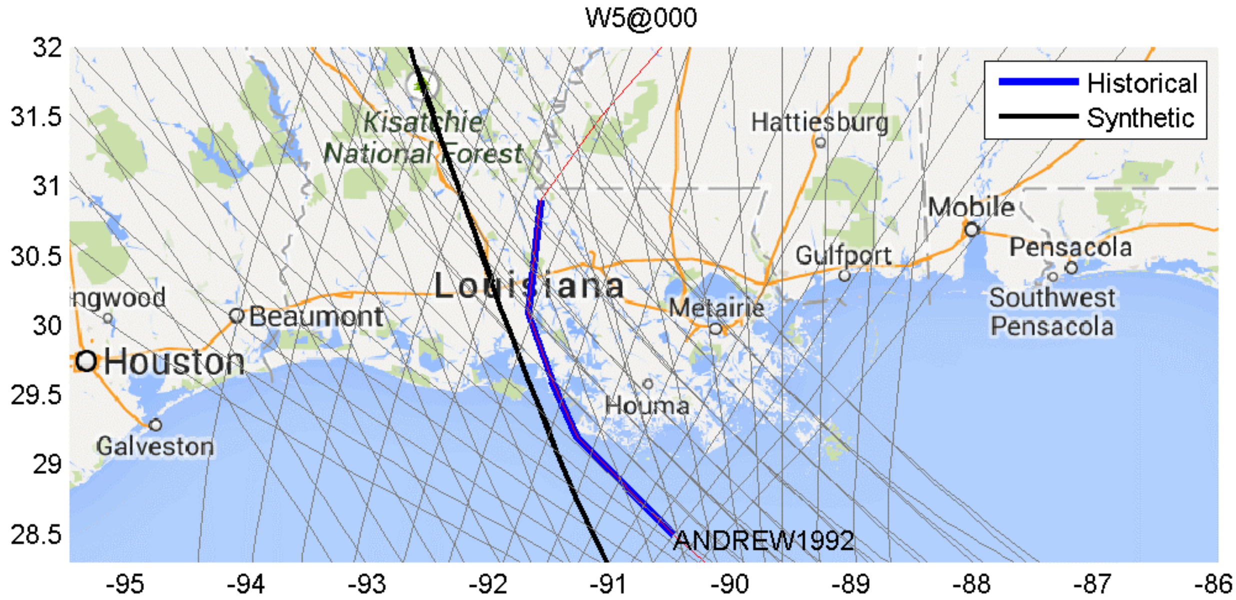


Tropical Storm Florence moved north toward Louisiana and became a hurricane on the 9th. Hurricane Florence struck Port Eads on the 10th and turned toward northwest. Highest rain total with the system was 4.47" at Abita Springs Fire Tower. Significant beach erosion occurred along Grand Isle. The inland part of Hurricane Florence follows the synthetic storm track of E3B@-45 well. However, only one storm (Storm 568) out of all that follow this track attains a central pressure (975 mb) closer to the historical record (982 mb). Storm 568 however moves slow (6 knots) in comparison to the historical forward speed (12.2 knots).

Table D10. Hurricane Florence Dynamic Parameters.

FLORENCE (1988)	Category	Offshore Cp (mbar)	Forward speed (knots)	Maximum wind speed (knots)	Size (nm)	Landfall time
History	H1	982	12	70	NA	9/10/1988 02:00
Storm 568	H1	975	6	67	17.7	28-Jul-2100 17:00:00 + 75.5 hrs

Figure D10. August 26, 1992 (Andrew).

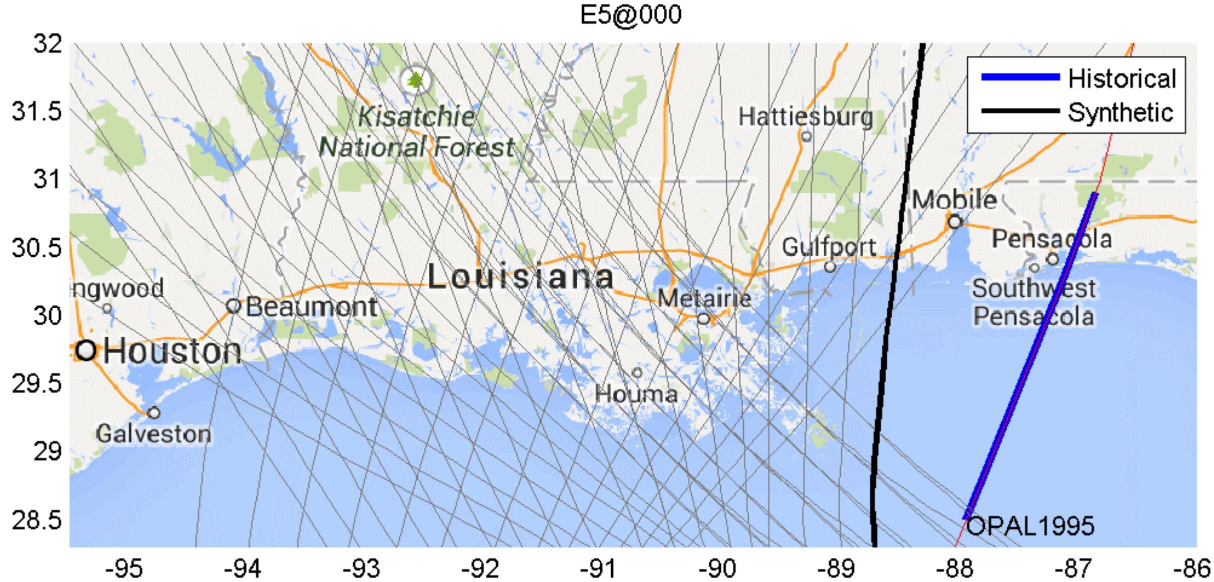


Hurricane Andrew struck coastal Louisiana on August 26th after it slammed south Florida. Rainfall totals from Andrew exceeded 5 inches over a four day period from August 24-28 in many locations with Robert receiving 11.02" and Hammond receiving 11.92". The highest surge reported was at 6.48 feet at Bayou Dupre. The storm track falls in between synthetic tracks of W5@000 and E1@000. Choosing the track of W5@000, the central pressure of 930 mb and the forward speed of 11 knots, yields three candidate synthetic storms that have various sizes, 8 nm, 17.7nm and 25.6nm, respectively. The largest one (Storm 242) is selected.

Table D11. Hurricane Bob Dynamic Parameters.

ANDREW (1992)	Category	Offshore Cp (mbar)	Forward speed (knots)	Maximum wind speed (knots)	Size (nm)	Landfall time
History	H4-5	937	9	135	NA	26-Aug-1992 0830
Storm 242	H3	930	11	100	25.8	29-Jul-2047 03:00:00 + 70.5hrs

Figure D11. October 4, 1995 (Opal).

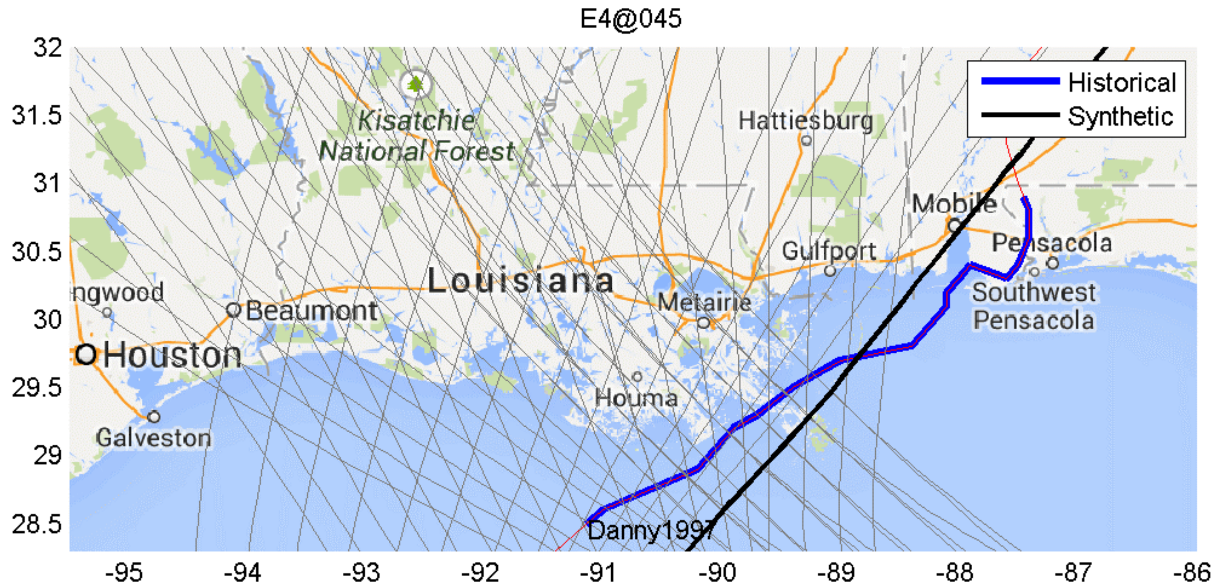


Hurricane Opal passing 150 miles off the Mississippi Delta made landfall in Pensacola, Florida. Rainfall amounts were greater than two inches across southeast Louisiana. No synthetic storm track in Louisiana JPM-OS suite can match Hurricane Opal. The closet one is the track of E5@000. A storm following this track but of a higher central pressure (930 mb) in comparison to the historical record of 916 mb is selected to represent Hurricane Opal.

Table D12. Hurricane Opal Dynamic Parameters.

OPAL (1995)	Category	Offshore Cp (mbar)	Forward speed (knots)	Maximum wind speed (knots)	Size (nm)	Landfall time
History	H3	916	21	110	NA	4-Oct-1995 2200
Storm105	H3	930	17	109	17.7	30-Jul-2110 02:00:00 + 46.0 hrs

Figure D12. July 17-18, 1997 (Danny).

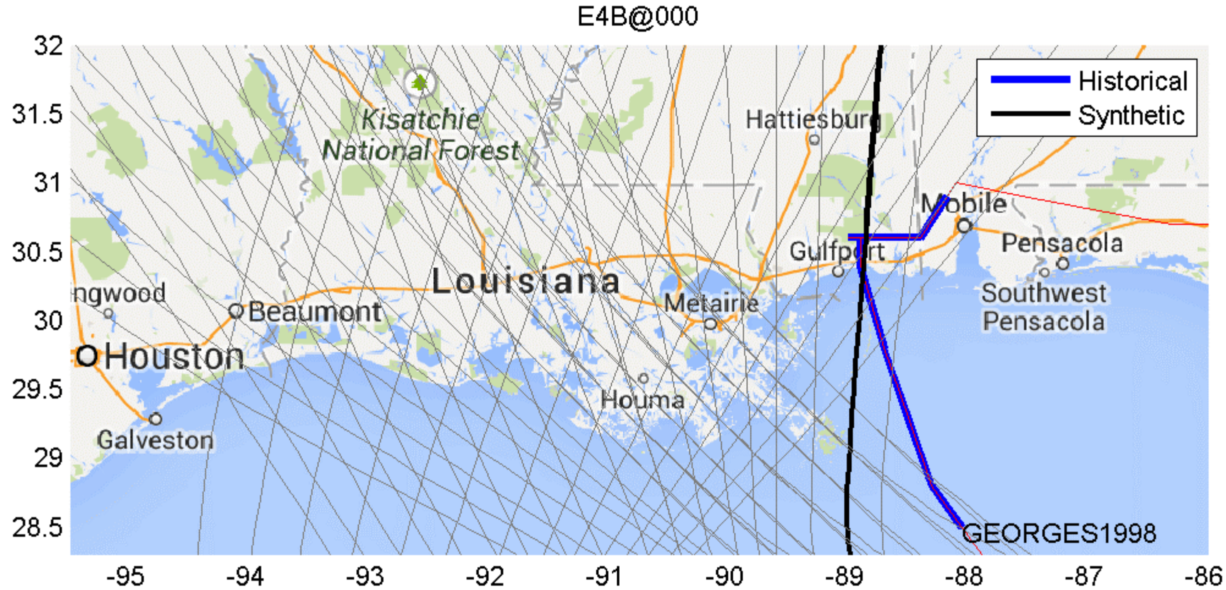


Danny became a hurricane on the July 18th and made landfall at Dauphin Island, Alabama passing through the Mississippi Delta. Averagely the synthetic track of E4@+45 aligns well with the historical storm track. Storm 544 follows this track and moves at the speed of 6 knots, which is still faster than Hurricane Danny. Hurricane Danny nearly stalled at the coast, with an average forward speed of 3.5 knots. Unfortunately, the slow motion cannot be accounted for by any synthetic storm.

Table D13. Hurricane Danny Dynamic Parameters.

DANNY (1997)	Category	Offshore Cp (mbar)	Forward speed (knots)	Maximum wind speed (knots)	Size (nm)	Landfall time
History	H1	984	3	70	NA	18-Jul-1997 0900
Storm 544	H1	975	6	67	17.7	28-Jul-2105 01:00:00 + 91.5hrs

Figure D13. September 27-28, 1998 (Georges).

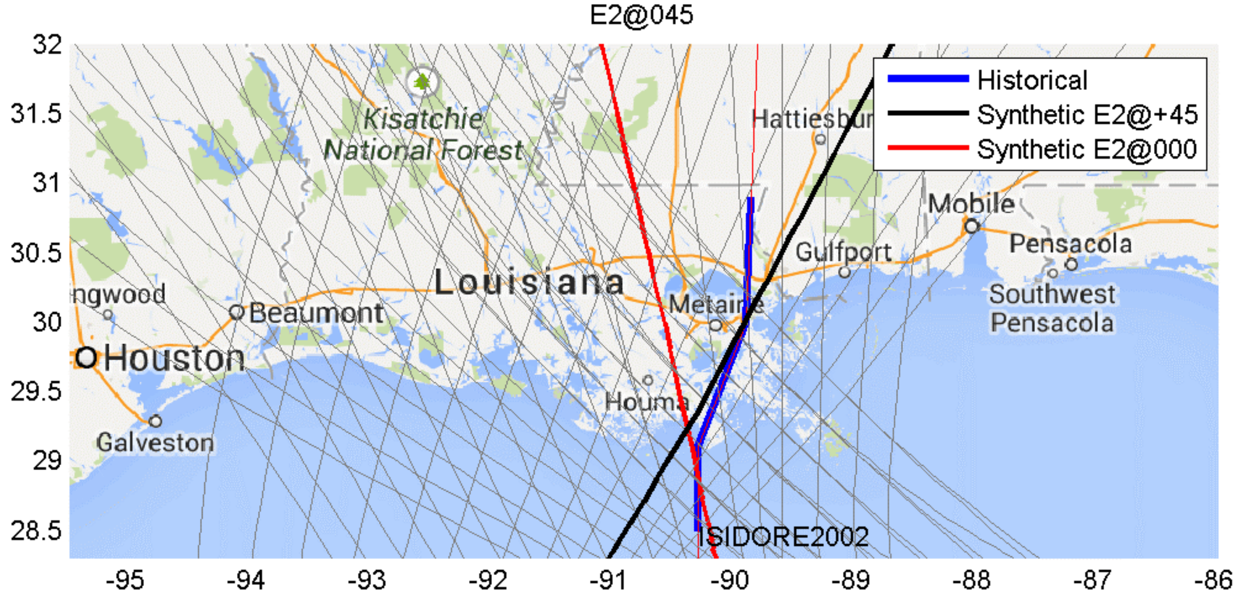


Hurricane Georges made landfall at Gulfport, Mississipi, and then turned east. Hurricane Georges stalled at the coast. Storm 090 is selected to align the historical storm, although it still moves faster than the real storm. Note that only the storm history between latitudes 28.5 and 31.0 is used for matching. The wind and pressure values listed are the value within that region.

Table D14. Hurricane Georges Dynamic Parameters.

GEORGES (1998)	Category	Offshore Cp (mbar)	Forward speed (knots)	Maximum wind speed (knots)	Size (nm)	Landfall time
History	H2	961	4	95	NA	28-Sep-1998 1130
Storm 143	H1	960	6	78	17.7	26-Jul-2148 12:00:00 + 132.0hrs

Figure D14. September 23-27, 2002 (Isidore).

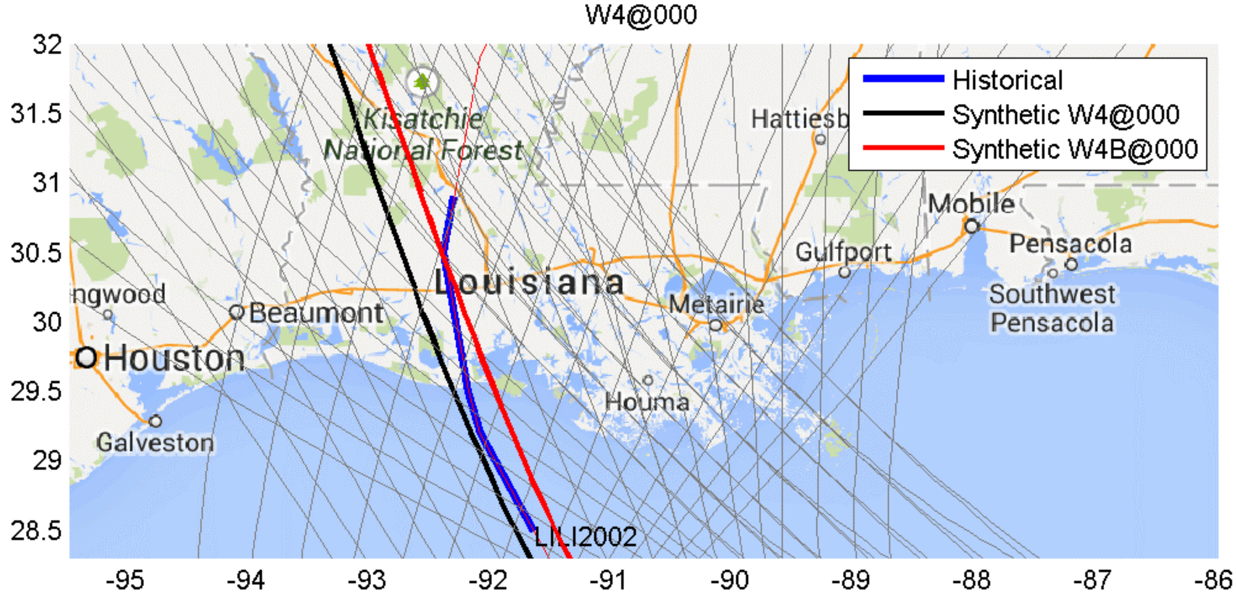


Hurricane Isidore made landfall west of Grand on September 26th. The track of Isidore before landfall aligns with the synthetic storm track of E2@000 while it turned toward east aligning with the track of E2@+45 in Louisiana. Storm 071 is selected following E2@+45.

Table D15. Hurricane Isidore Dynamic Parameters.

ISIDORE (2002)	Category	Offshore Cp (mbar)	Forward speed (knots)	Maximum wind speed (knots)	Size (nm)	Landfall time
History	H1	960	14	55	NA	26-Sep-2002 0600
Storm 071	H1	960	11	82	24.6	28-Jul-2076 + 95.5hrs

Figure D15. October 2-5, 2002 (Lili).

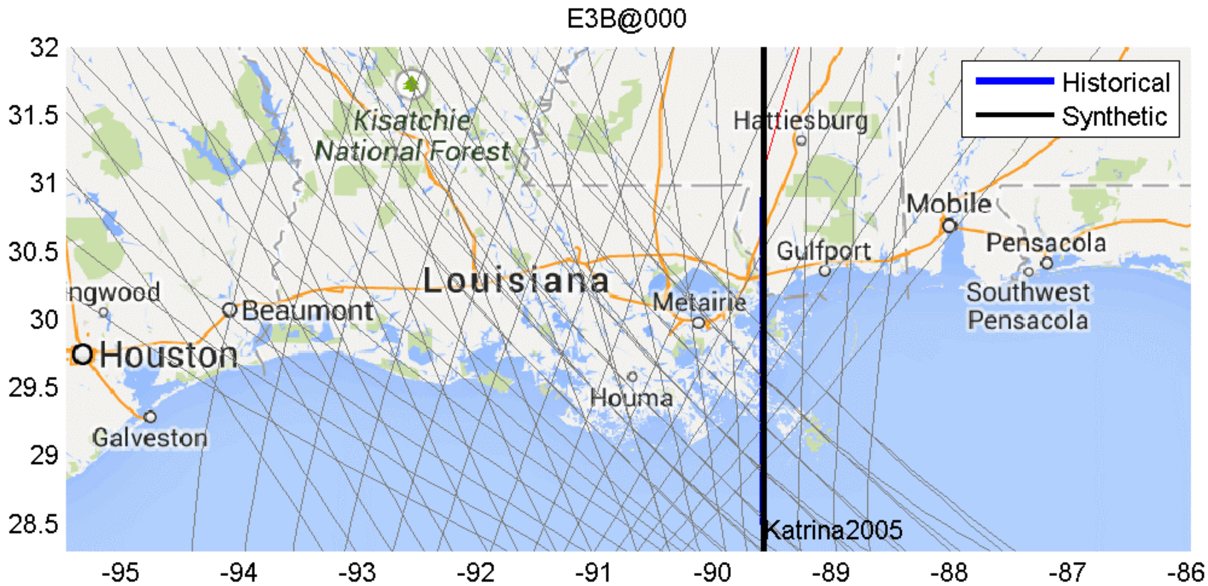


Hurricane Lili moved fast when approaching coastal Louisiana, averagely 13 knots and made landfall at central Louisiana. Two synthetic storm tracks, W4@000 and W4B@000 potentially can be used as analogs of the real track. The track of W4@000 is generally closer to the actual track. Storm 233 following the track (W4@000) that is to the west of the real one is selected to approximate the historical event.

Table D16. Hurricane Lili Dynamic Parameters.

LILI (2002)	Category	Offshore Cp (mbar)	Forward speed (knots)	Maximum wind speed (knots)	Size (nm)	Landfall time
History	H3	938	13	105	NA	3-Oct-2002 1300
Storm 233	H3	930	11	100	25.8	29-Jul-2038 02:00:00 + 70.0 hrs

Figure D16. August 29, 2005 (Katrina).



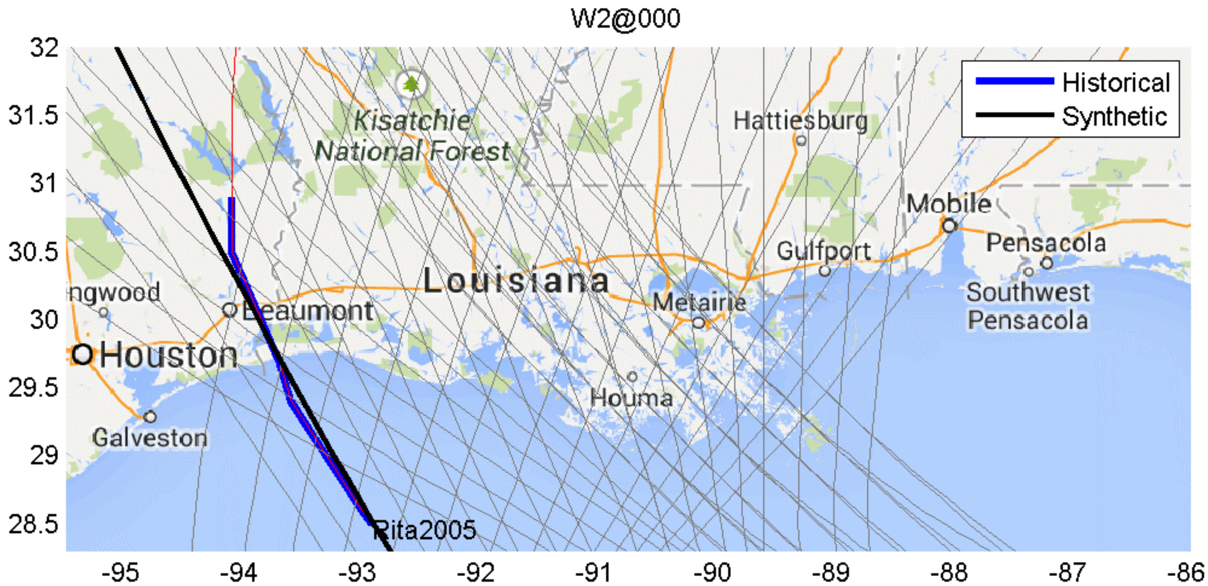
Katrina emerged, strengthened in the Gulf of Mexico, and reached Category 5 on August 28th. The synthetic track of E3B@000 aligns well with the real track. Storm 120 that follows this track is selected. However it is worth noting that the synthetic Storm 120 is less intense than the real event, although it is the closest match. The forward speed of the synthetic storm moves slower than the historical record, which might be compensatory for the smaller size and lower wind strength of the selected synthetic storm.

Note that only the storm history between latitudes 28.5 and 31.0 is used for matching. The wind and pressure values listed are the value within that region.

Table D17. Hurricane Katrina Dynamic Parameters.

KATRINA (2005)	Category	Offshore Cp (mbar)	Forward speed (knots)	Maximum wind speed (knots)	Size (nm)	Landfall time
History	H4-5	913	15	125	NA	29-Aug-2005 11:10
Storm120	H3	900	11	113	17.7	29-Jul-2125 01:00:00 + 71.0hrs

Figure D17. September 23-25, 2005 (Rita).

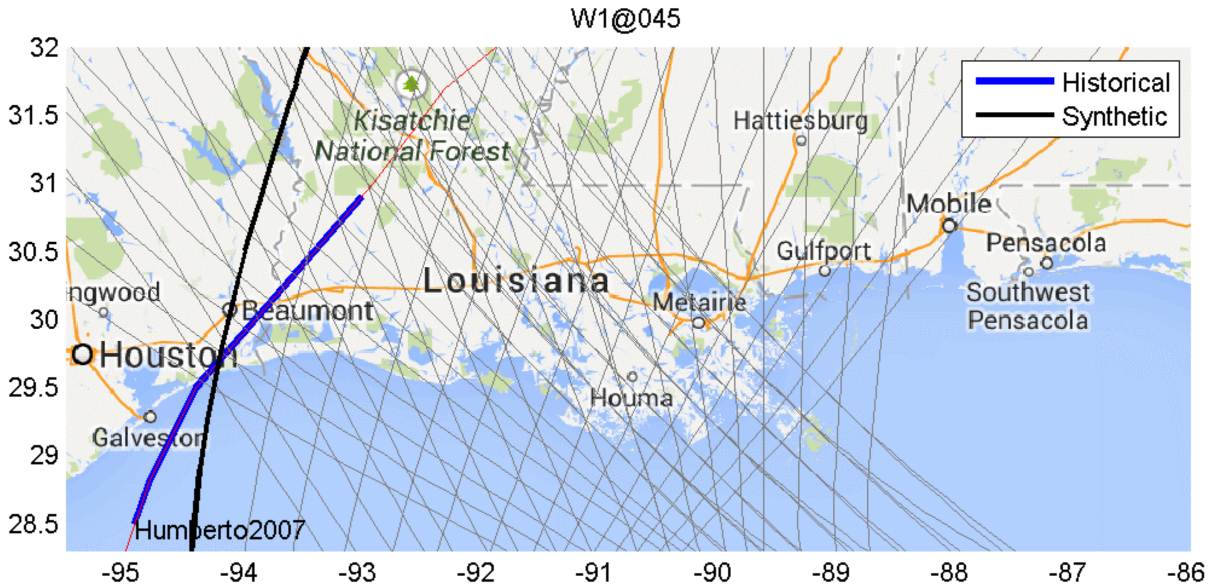


Hurricane Rita devastated extreme southeast Texas and southwest Louisiana. Heavy rains fell near and east of the track of the hurricane, with the highest total in Louisiana recorded at Bunkie, where 16 inches fell. The synthetic storm track of W2@000 represents the historical track well. Among storms that follow this track, Storm 218 matches the features of low central pressure and forward speed closely, thus selected as the analog.

Table D18. Hurricane Rita Dynamic Parameters.

RITA (2005)	Category	Offshore Cp (mbar)	Forward speed (knots)	Maximum wind speed (knots)	Size (nm)	Landfall time
History	H3	895	11	105	NA	24-Sep-2005 07:40
Storm 218	H3	900	11	111	21.8	29-Jul-2023 02:00:00 + 69.5hrs

Figure D18. September 13-14, 2007 (Humberto).

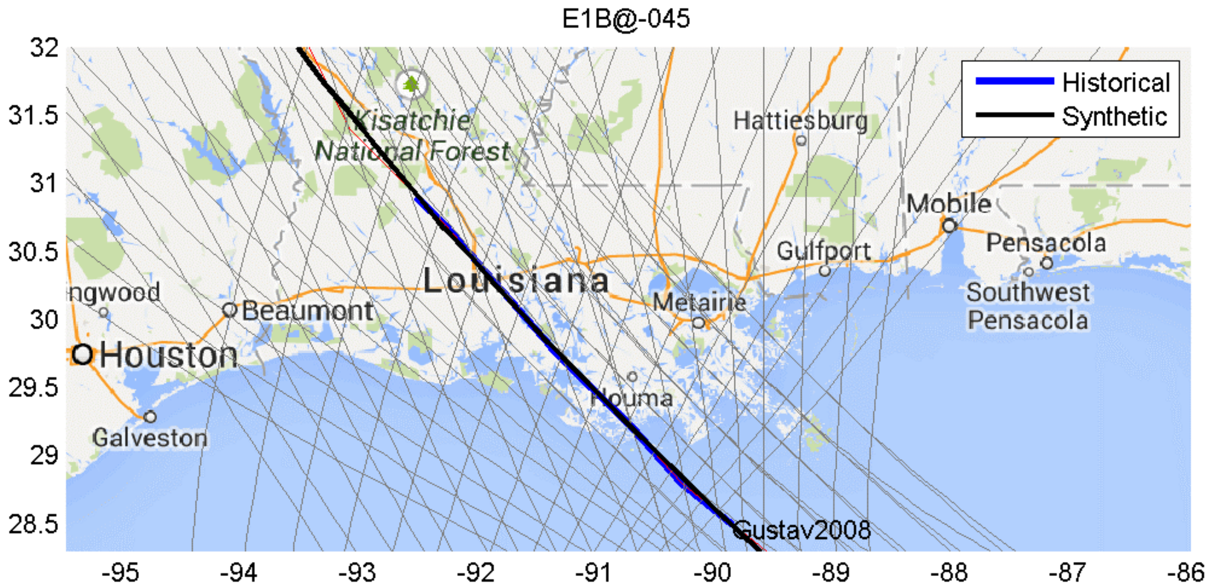


Hurricane Humberto made landfall in Texas and moved to Louisiana, weakening slowly. The closest match of this storm is Storm 424 that follows the historical track but less tilted toward east.

Table D19. Hurricane

Table D18. Hurricane Humberto Dynamic Parameters						
HUMBERTO (2007)	**Category**	**Offshore Cp (mbar)**	**Forward speed (knots)**	**Maximum wind speed (knots)**	**Size (nm)**	**Landfall time**
History	H1	985	9	80	NA	13-Sep-2007 07:00
Storm 424	H1	975	11	75	18.2	28-Jul-2071 01:00:00 + 95.0 hrs

Figure D19. August 31-September 3, 2008 (Gustav).

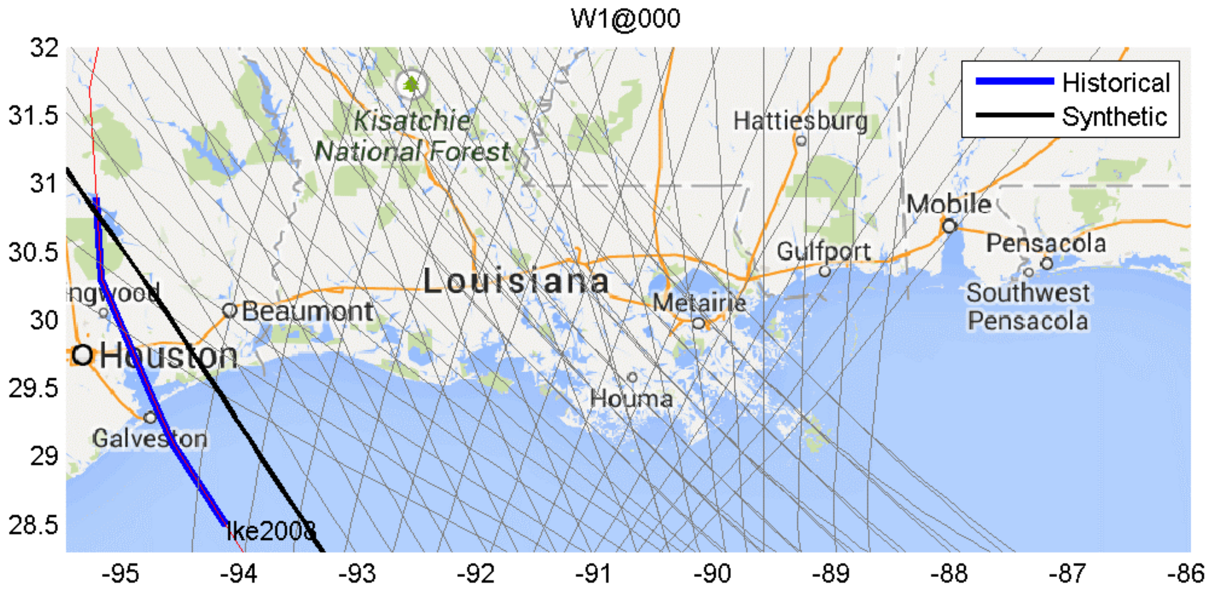


A combination of land interaction with western Cuba and an upper level low to its west kept Gustav on a slow weakening trend until its final landfall in southeast Louisiana on September 1st. The system slowed to a crawl across northwest Louisiana and southwest Arkansas on the 2nd and 3rd, dropping heavy rainfall across east-central Louisiana, Arkansas, and southwest Mississippi. Heavy rains fell along and east of its track within east-central and south-central Louisiana and western Mississippi, with the highest total measured of 21 inches at Larto Lake. The synthetic storm track of E1B@-45 trails the real track closely. Storm 123 is found to be the closest analog of the historical event with the similar features of central pressure and forward speed.

Table D20. Hurricane Gustav Dynamic Parameters.

GUSTAV (12008)	Category	Offshore Cp (mbar)	Forward speed (knots)	Maximum wind speed (knots)	Size (nm)	Landfall time
History	H2	954	13	95	NA	1-Sep-2008 15:00
Storm 123	H2	960	11	85	17.7	29-Jul-2055 19:00:00 + 52.5hrs

Table D20. September 12-14, 2008 (Ike).

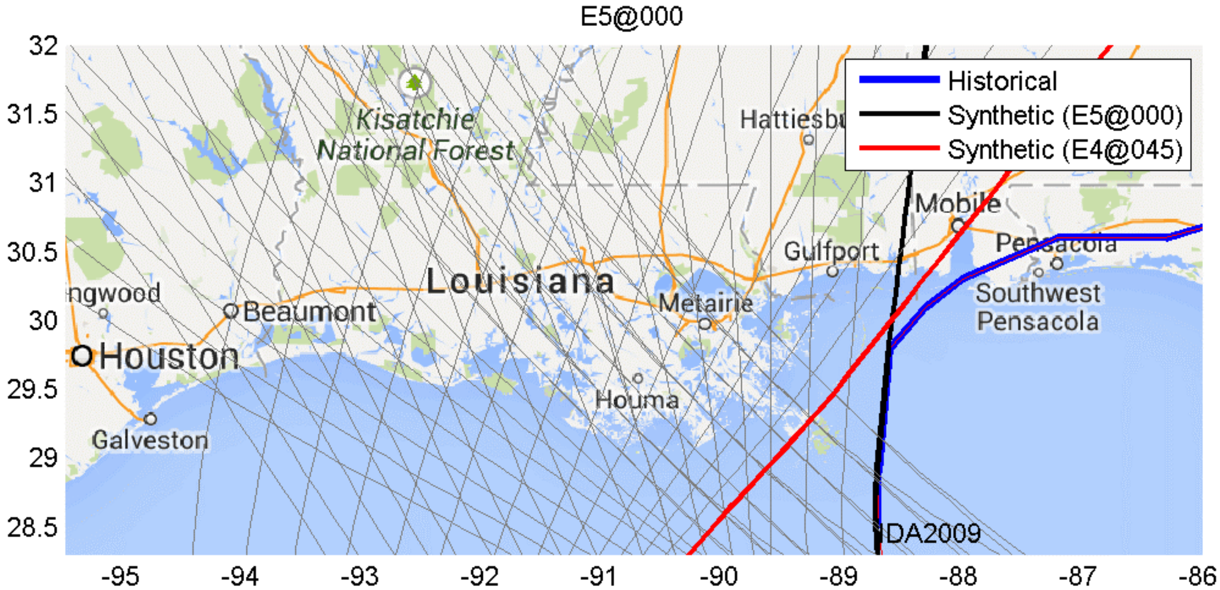


Hurricane Ike made landfall in Galveston, TX, and the track is parallel with the synthetic track of W1@000. Storms 204-206 follow this track and present a similar forward speed but a bit lower central pressure of 930 mb in comparison to the actual value of 944 mb. To compensate for the big differences in track and central pressure, Storm 204 with a smallest radius of maximum wind (8 nm) is selected as the analog.

Table D21. Hurricane Ike Dynamic Parameters.

IKE (2008)	Category	Offshore Cp (mbar)	Forward speed (knots)	Maximum wind speed (knots)	Size (nm)	Landfall time
History	H2	944	12.3	95	NA	13-Sep-2008 0700
Storm 204	H3	930	11.0	100	8	29-Jul-2009 02:00:00 + 70.0hrs

Figure D21. November 04-11, 2009 (Ida).

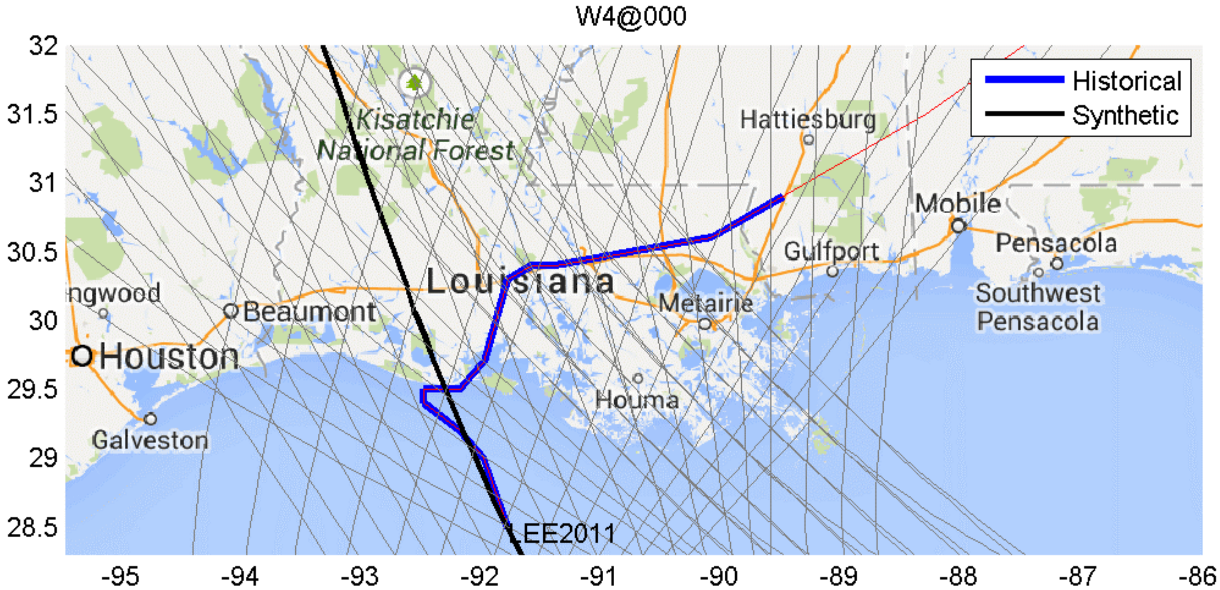


Hurricane Ida moved northward in the Gulf and sharply turned east when it approached the coast. It made landfall in Mobile Bay, Alabama and weakened quickly to a tropical depression. The synthetic tracks of E5@000 and E4@+45 align well in the gulf and over land, respectively. To represent the offshore water level, Storm 513 following the track of E5@000 is selected.

Table D22. Hurricane Ida Dynamic Parameters.

IDA (2009)	Category	Offshore Cp (mbar)	Forward speed (knots)	Maximum wind speed (knots)	Size (nm)	Landfall time
History	H1	975	8	75	NA	10-Nov-2009 09:00
Storm 513	H1	975	11	77	11.0	29-Jul-2042 02:00:00 + 70.0hrs

Figure D22. September 2-6, 2011 (Lee).

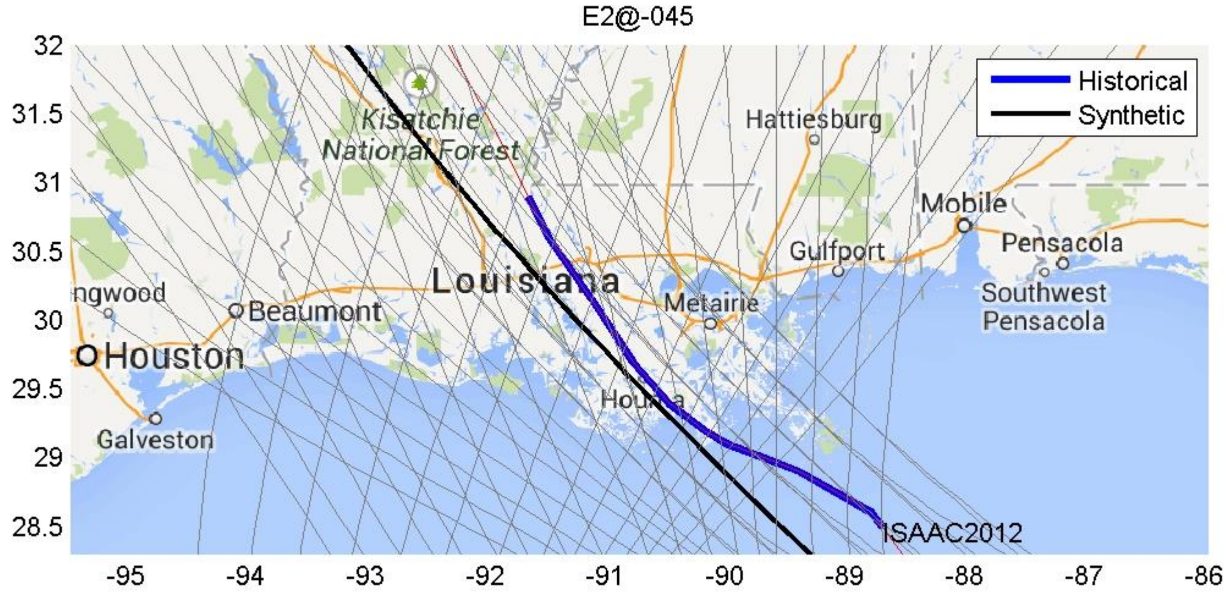


Tropical Storm Lee presented a larger size and moved northward slowly. Heavy rainfall occurred in southern Louisiana, Mississippi, Alabama, and the Florida panhandle. Flooding associated with the rains caused significant property damage in the areas. Because of the meandering of the real track, no matching synthetic storm track can be found. Synthetic tracks, W4@000, W4@+45 and W3B@+45 are candidate analog tracks, among which W4@000 maintains well the offshore track and the other two parallel to the direction of the actual track over land. Storms 435, 444, and 471 follow those three tracks, respectively with other parameters remained the same. Per the selection of track W4@000, Storm 435 is recommended.

Table D23. Hurricane Lee Dynamic Parameters.

LEE (2011)	Category	Offshore Cp (mbar)	Forward speed (knots)	Maximum wind speed (knots)	Size (nm)	Landfall time
History	TS	986	5	50	NA	4-Sep-2011 10:30
Storm 435	H1	975	6	67	17.7	26-Jul-2093 13:00:00 + 131.5hrs

Figure D23. August 29, 2012 (Isaac).



Hurricane Isaac came ashore in Louisiana on August 29th and moved through Louisiana slowly. The slow-moving rainbands dropped heavy rains in localized area. Two tracks, E2@-45 indicated in the figure and E2B@-45 to the east of the indicated track, follow the actual track generally well. However no storm following those tracks presents similar central pressure of 965 mbar nor moves at the speed of 6 knots. To maintain the feature of track and central pressure, Storm 51 following the track of E2@-45 can be selected, which retains other features of Isaac except the forward speed. Alternately, Storm 93 and Storm 538 both follow track of E2@-45 and move at the speed of 6 knots, however Storm 93 and Storm 538 have central pressure of 930 mbar and 975 mbar, respectively. Storm 538 is recommended here since Hurricane Isaac was a relatively low-intensity storm. Other storms are also listed here for reference.

Table D24. Hurricane Isaac Dynamic Parameters.

ISAAC (2012)	Category	Offshore Cp (mbar)	Forward speed (knots)	Maximum wind speed (knots)	Size (nm)	Landfall time
History	H1	965	6	70	NA	29-Aug-2012 08:00
Storm 538	H1	975	6	67	17.7	28-Jul-2098 06:00:00 + 90.5hrs
Storm 93	H3	930	6	95	17.7	28-Jul-2098 05:00:00 + 91.5hrs
Storm 51	H2	960	11	85	24.6	29-Jul-2056 19:00:00 + 53.5hrs