P2H.8 **LANDFALLING TROPICAL CYCLONES IN THE EASTERN PACIFIC. PART I: CASE STUDIES FROM 2006 AND 2007.**

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1. INTRODUCTION

Western Mexico routinely experiences landfall of tropical cyclones. Jáuregui (2003) documented that 65 hurricanes approached the west coast and 60% of them made landfall in the northwestern part of the country between 1951 and 2000. This area is located north of 20ºN and west of 105ºW, which includes the Baja California Peninsula and the States of Nayarit, Sinaloa and Sonora. Also, 64% of 88 tropical storms entered this area, increasing precipitation in this very arid region. Some of these systems continued moving northward after landfall and, eventually, had an influence on the weather conditions in the southwestern United States.

The records for the eastern Pacific basin, provided by the National Hurricane Center, reveal 614 tropical cyclones during 1970–2007. Figure 1 displays the tracks of the sub-group of tropical cyclones that made landfall over northwestern Mexico. The upper panel (Fig. 1a) shows the 27 tracks that moved over the Baja California Peninsula, with nine of them crossing the Gulf of California and reaching the mainland. The incident storms approached the peninsula from the south and most of the landfall storms occurred from late August through early October. The inserts in the figures show the temporal frequency, determined by dividing each month into three periods of 10 or 11 days.

Twenty-five tropical cyclones tracked over the mainland during this 38-year period, shown in Figure 1b. In contrast to the storms that went across the peninsula, those that moved onto the mainland acquired a significant eastward component by 20ºN. Additionally, most storms developed late in the season with highest frequency during the last two-thirds of September (35%) and all of October (54%). In a study of the period 1966-2004, Romero-Vadillo et al. (2007) identified this type of storm track and the landfall trend associated with the presence of westerly airflow at middle and upper levels.

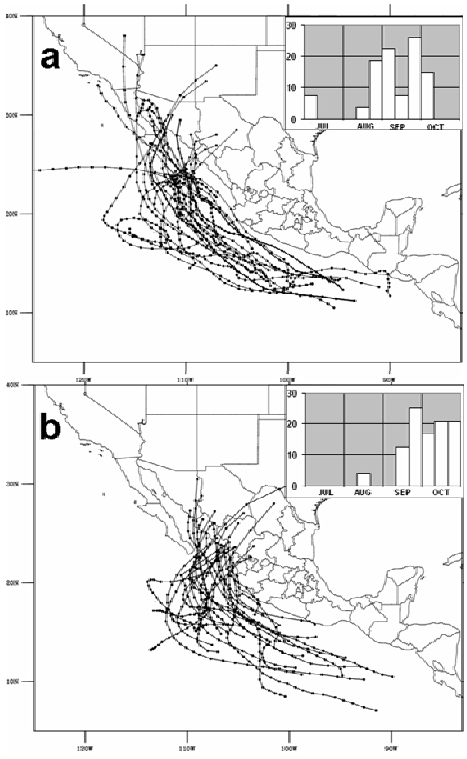

Figure 1. Tracks of tropical cyclones that made landfall over (a) the Baja California peninsula and (b) the mainland of northwestern Mexico. Tracks are for the period 1970-2007 and positions are shown at 6-h intervals. Frequency (%) of landfall activity is shown in the upper-right inserts for 10 or 11 day periods.

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Activity during the 2006 tropical cyclone season (May–November) was above average, with 18 named systems in the Eastern Pacific Basin (Pasch and Blake, 2007). Ten of these systems reached hurricane intensity. These numbers are only slightly higher than the records cited by Arguez (2007): 16.4 tropical storms and 9.6 hurricanes. In 2006, three systems made landfall in northwestern Mexico: John, Lane, and Paul.

Figure 2 shows John's track landing at the southern part of the peninsula in early September and Lane and Paul moving across the southeastern coast of the Gulf of California, north of Mazatlán in mid-September and late October, respectively. Tropical Cyclone Henriette (2007) made landfall at the southern part of the peninsula, then crossing the Gulf of California, and landing in the State of Sonora. John and Henriette had tracks and landfall similar to those shown in Fig. 1a and Lane and Paul had tracks and landfall similar to those shown in Fig. 1b. These events brought strong winds and heavy rainfall, with extensive property damage and flooding reported by communities throughout the affected area.

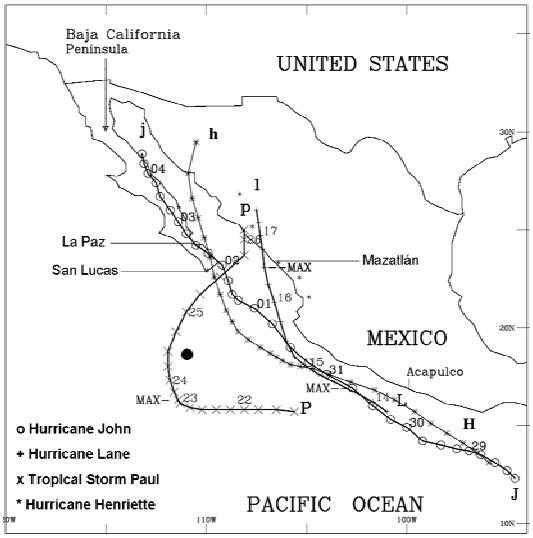

Figure 2. Tracks of Tropical Cyclones: John, Lane and Paul in 2006 and Henriette in 2007. Initial positions are represented by uppercase letters and final positions by lowercase letters. Position location is marked every 6 hours; numbers are fixes at 0000 UTC; and position at maximum intensity (MAX) is indicated. The large black dot represents Isla Socorro.

This study examines the life cycle of tropical cyclones that made landfall in Mexico during the 2006 and 2007 seasons; however we focus on documenting the landfall of tropical cyclones John and Henriette over the Baja California Peninsula and Lane and Paul over mainland Mexico. In particular, we discuss the following aspects:

- Storm motion, along with information from large-scale analyses,
- Rainfall accumulations derived from local stations, and
- Convective structures detected by the geostationary satellite.

2. DATA SOURCES

Digital imagery from the *Geostationary Operational Environmental Satellite-11* (*GOES-11*) is used to document the structure of cloud cover. We use infrared and visible channels with spatial and temporal resolution of 4 km and 30 min, provided by the University Corporation for Atmospheric Research (UCAR) through the Unidata Program Center in Boulder, Colorado.

To determine patterns and intensity of significant rainfall events, data from the Mexican network of rain gauges managed by Comisión Nacional del Agua (CNA) are used. These records are available as 24-h totals ending at 1500 UTC. Information on the three-dimensional structure of the large-scale flow is derived from the gridded analyses of the Global Forecast System (GFS) model, operated by the U.S. National Centers for Environmental Prediction (NCEP), which are available at 100×100 km grid resolution.

3. RESULTS

3.1 Hurricane John

Tropical Cyclone John was active from 28 August through 4 September 2006. This system was first detected (Tropical Depression 11-E) southeast of Acapulco (Fig. 2). While moving northwestward, it was upgraded to a hurricane and the GFS analyses indicated

that a mid-level, anticyclonic circulation was centered over northeastern Mexico (A in Fig. 3a). The southwest flank of this feature was associated with steering currents from the southeast and storm displacement parallel to the Pacific and Baja California Peninsula coastlines. Additionally, air with enhanced moisture (precipitable water > 30 mm) was advected into northwestern Mexico and the southwestern United States. These were favorable conditions for John's development along the peninsula.

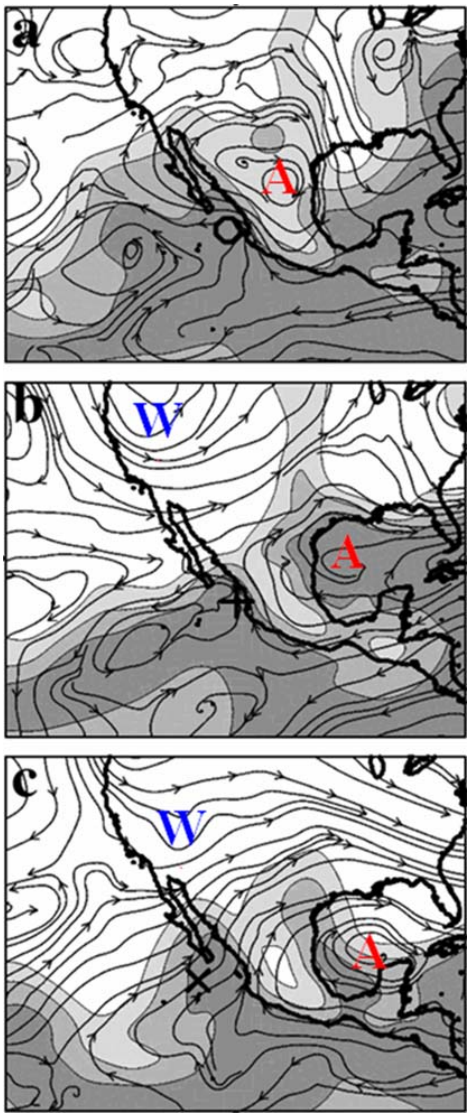

Figure 3. Streamlines at the 500-mb level and precipitable water (mm) from the GFS analyses in 2006 at (a) 0000 UTC 1 September; (b) 0000 UTC 16 September; and (c) 0000 UTC 25 October 2006. Shading represents values above 30 mm in increments of 10 mm.

Figure 4a is a satellite image at landfall, east of San Lucas, in which a well-defined area of deep convection (cloud-top temperature <–70ºC) was located around the circulation center. The corresponding visible image (not shown) included spiral bands, consistent with intense convection. An estimate of rainfall accumulations during the passage of the storm is based on the regional rain-gauge network from 30 August to 4 September, which includes the approach, landfall, and passage over the peninsula. Table 1 shows total precipitation at selected stations along the southeastern peninsula and mainland coast.

Station	John	Lane	Paul	Jul-Oct
Loreto, B.C.S.	265	0	57	355
La Paz, B.C.S.	79	0	2	169
San Lucas, B.C.S.	129	0	36	308
Choix, Sin.	75	0	50	573
Pericos, Sin	14	16	224	738.2
Mazatlán, Sin.	89	257	32	1001
Acaponeta, Nay.	98	154	18	989
Tepic, Nay.	27	28	36	898

Table 1. Rainfall accumulations (mm) at eight sites from three 2006 tropical cyclones: John (31 August–4 September), Lane (15–17 September), and Paul (24–26 October) and the warm season accumulation (1 July – 31 October).

Moderate rainfall was recorded by stations along the mainland with a 98-mm maximum at Acaponeta in the state of Nayarit. La Paz, San Lucas, and Loreto in the southern half of the peninsula received a significant contribution from John, compared to accumulations from Lane and Paul that had only a small affect on the peninsula. Note that these contributions represent between 42 and 75% of the accumulated precipitation during the warm season (July though October) of 2006 at specific stations. Furthermore, inspection of daily precipitation records indicated that most of these accumulations occurred in a 24–72 h period.

3.2 Hurricane Lane

In contrast to John, Lane was associated with a lack of measurable rainfall from 13 to 17 September 2006 over most of the peninsula. This agrees with the dry air mass (precipitable water <30 mm) over most of northwestern Mexico and with limited convection. The large-scale analysis shows that a wave trough was propagating into the western United States (W in Fig. 3b). This configuration results in relatively dry and cool air being advected into the area of study.

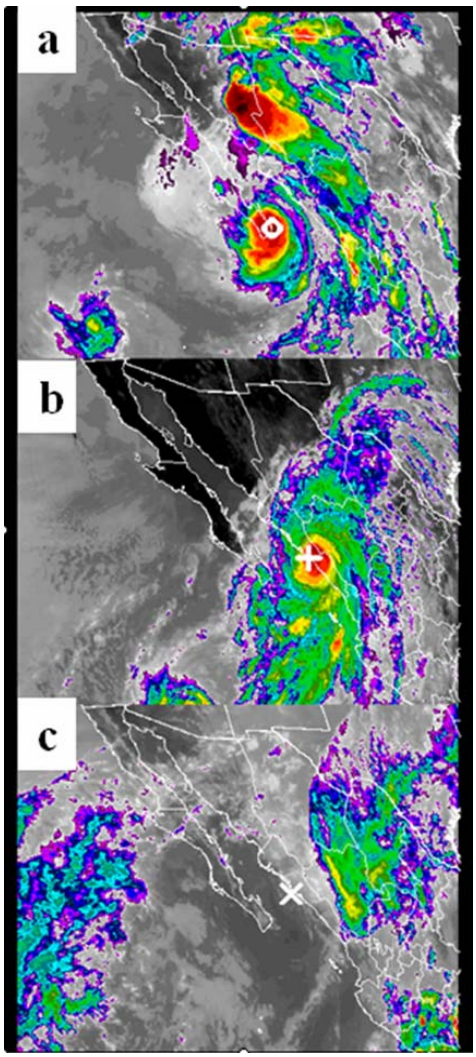

Figure 4. Cloud-top temperature (ºC) from GOES-11 infrared satellite imagery. Images are from (a) 0200 UTC 2 September; (b) 1800 UTC 16 September; and (c) 0000 UTC 26 October 2006. The ○, +, and × indicate positions of the circulation center for John, Henriette and Paul, respectively. Red represents areas below -70ºC.

Another feature of interest from Fig. 3b is the location of an anticyclonic circulation over the Gulf of Mexico. This circulation is consistent with mid-level, steering flow from the south and Lane's northward displacement onto the mainland across the Sierra Madre Occidental (Fig. 2). The configuration of the flow over northwestern Mexico corresponds to the mean structure of middle to upper level westerly flow for September (Romero-Vadillo et al. 2007).

Figure 4b shows the satellite image at landfall north of Mazatlán, in which deep convection was located around the circulation center. Table 1 shows the storm's precipitation totaling 257 mm at Mazatlán followed by a close second in total at Acaponeta. These accumulations are related to closeness of the storm track to the coastline and to a more intense core, compared to the approach of John (Fig. 2). At landfall, John was a Category 2 hurricane (49 m s^{-1}), while Lane was a Category 3 hurricane (57 m s^{-1}) on the Saffir-Simpson scale.

3.3 Tropical Storm Paul

Paul was present from 21 through 26 October 2006 and followed a storm track similar to the recurving cases shown in Fig. 1b. After 24 October, the storm acquired an eastward zonal motion, resulting in landfall north of Mazatlán (Fig. 2). The system was classified as a weakening tropical depression at landfall. Note the absence of organized convection in the satellite image (Fig. 4c).

In spite of Paul's intensity, a relatively large accumulation (224 mm) was reported at Pericos, Sinaloa, where the precipitation contributed 30% of the total accumulation for the entire warm season of 2006, most of the rainfall occurring in the day prior to landfall. Animated satellite imagery was used to determine that intense cloud clusters developed ahead of the center of circulation. The large-scale fields from the GFS analysis suggest that the cloud clusters and moist air mass were advected onto the mainland by the middle level flow from the equatorial Pacific (Fig. 3c). As in Lane's landfall, there is an anticyclonic circulation centered in the Gulf of

Mexico, along with a wave trough over the southwestern United States.

3.4 Hurricane Henriette

Henriette was the only hurricane that made landfall during the relatively inactive 2007 season (Avila and Rhome, 2008). During this season, only 11 named systems developed.

Figure 2 shows the corresponding storm track along with the two landfall events in northwestern Mexico. The first event was over the southern part of the peninsula, Category 1 hurricane (35 m s^{-1}) and the second one in Sonora, as a weakening tropical storm. While heading toward northwestern Mexico, there was an anticyclonic circulation centered over the northern Gulf of Mexico (Fig. 5a). This configuration of airflow is consistent with Henriette's northward motion and enhanced humidity over the southern Gulf of California. The presence of another anticyclonic circulation over the southwestern United States vanished during the landfall events.

Figures 5b and 5c show satellite imagery at landfall, in which deep convection was located around the circulation center. The first event occurred just east of San Lucas and was associated with heavy rainfall during 4–5 September over the southeastern edge of the peninsula. Records from the CNA network indicate that maximum accumulations, in the range of 400–500 mm, were recorded at stations higher than 350 m. In contrast, the coastal sites of San Lucas, La Paz, and Loreto received more limited accumulated rainfall, below 160 mm.

4. SUMMARY

The goal of this study is to document the tracks of tropical cyclones that made landfall in northwestern Mexico. Based on the NHC best-track positions, four storm systems were selected for analysis: John, Lane, and Paul in 2006 and Henriette in 2007. These systems brought strong winds, deep convection, and heavy rainfall to communities in the Baja California Peninsula and mainland Mexico. Analyses of the GFS model identified significant features in the large-scale flow during the approach of each storm system.

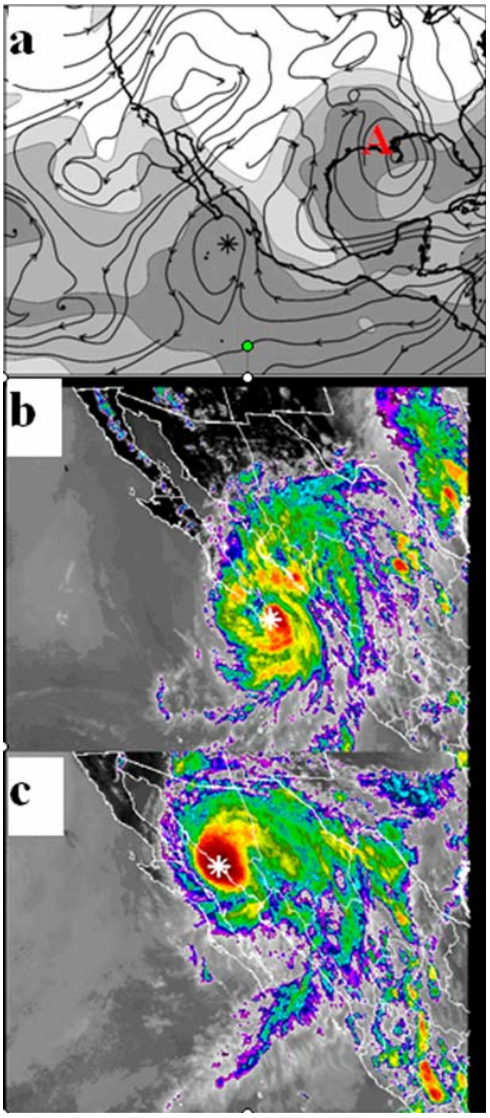

Figure 5. Hurricane Henriette in September, 2007. (a) Streamlines at the 500-mb level and precipitable water (mm) from the GFS analyses at (a) 0000 UTC on the 4th. Shading represents values above 30 mm in increments of 10 mm; A represents the center of anticyclonic circulation. *GOES-11* images from (b) 2100 UTC on the 4th and (c) 0000 UTC on the 6th. The asterisk is the storm center.

Key findings from the study are the following:

- Hurricane John (2006) provided a well-defined period of heavy precipitation along the eastern coast of Baja California with contributions in the range of 42–75% of the accumulations received during the entire warm season.

- Hurricane Lane was the strongest system at the time of landfall (Category 3) over the mainland. However, the other cyclones also provided much of the precipitation accumulated during the season.
- Of the four cases, Tropical Storm Paul was the only recurving system and its track occurred under the influence of an anticyclonic circulation in the Gulf of Mexico, along with a wave trough that reached the southwestern United States.
- Advection of dry air over northwestern Mexico was associated with the absence of convective activity over the Baja California Peninsula; heavy rainfall was concentrated over the States of Nayarit and Sinaloa during the landfall of Hurricane Lane.
- Middle level advection of dry air, from troughs approaching the western United States, is an important element in predicting the tracks and rainfall of tropical cyclones making landfall.

A similar methodology to the one used in this study is currently being applied to the tropical cyclone seasons from 1970 through 2007. An examination of large-scale fields associated with landfall strikes over the Baja California Peninsula and over the mainland is now in progress. This expansion of case studies will increase our knowledge of the impact of storms over northwestern Mexico and will provide practical information for operational forecasters.

Acknowledgements

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