12.6 RELATIONSHIPS BETWEEN TROPICAL SYSTEMS AND RAINFALL IN THE BAJA CALIFORNIA PENINSULA, MEXICO

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1. INTRODUCTION

Among the weather systems that develop at low latitudes, Tropical Cyclones (TCs) are seasonal circulations that occur over relatively warm oceans. While this activity is limited to certain regions of the world, the eastern North Pacific Ocean produces the most TCs per unit area of any basin worldwide (Blake et al. 2009). The basin is north of the Equator, bounded by 140°W and the west coast of the Americas (see Figure 1). On average, more than 15 named TCs develop every season (e.g., Arnt et al. 2009) and the west coast of Mexico is especially vulnerable to circulations that move through the coastline (Serra 1971). From May through October, the TC development provides changes in moisture content and, under favorable conditions, this becomes a source of heavy rainfall over the coast and mountains.

Landfall is defined as the passage of the circulation center across the coastline and, eventually, the TC can produce strong winds, storm surge, and heavy rainfall with the potential to cause extensive property damage to the population. Northwestern Mexico (>21°N) has the highest frequency of landfall in the entire basin (Jáuregui et al. 2003). This region includes a portion of the mainland and the southern Baja California Peninsula (Blake et al. 2009). The latter is known as the state of Baja California Sur (BCS, see insert in Fig. 1) and it is approximately 700 km in length.

Features that create a unique meteorological situation in BCS include a narrow mountain range with elevations of 1-2 km, warm seawater (>25°C) in the Gulf of California, and the cold California Current (<20°C) in the adjacent Pacific Ocean. The peninsula is in a geographical position along the path of humid air masses, deep convection, and rainfall episodes that are associated with TCs from the Pacific basin (Farfán and Fogel 2007). The first regional study on the association between TCs and rainfall was performed by Latorre and Penilla (1988). These authors documented the contribution of rainfall from TCs that made landfall or approached the coast within 250 km.

In the present study, the influence of TCs in the rainfall patterns over BCS is examined. Impact is analyzed for the 40-year period from 1970 through 2009. Our goal is to identify patterns associated with the landfall of TCs. In addition, we consider the contribution from TCs that approached the coast close enough to provide significant rainfall accumulations.

2. DATA

The best-track database of TCs in the eastern North Pacific, compiled by the United States National Hurricane Center (NHC), provides a representation of position and intensity of the circulation center over its entire lifecycle (Rappaport et al. 2009). Because of limitations with other sources of observations such as reconnaissance aircraft, satellite imagery is the primary source to estimate TC positions and intensities. Since 1966, geostationary and polar-orbiting satellites have been providing continuous detection of TC activity in the basin (Gunther 1982).

Data from a ground-based network of rain gauges are used to determine spatial coverage and intensity patterns from selected TCs. The dataset is archived by Servicio Meteorológico Nacional (SMN) in Mexico, and individual station records are available as 24-hour totals. More than 100 stations in BCS are examined. In order to set a climatological reference, the daily records are also used to compute long-term averages and individual daily maxima at selected stations.

3. RESULTS

The examination of best-track records for the study basin reveals the development of 608 named TCs during the seasons from 1970 through 2009. This yields an annual average of 15.2. Figure 2 shows the basin frequency of named storms. Minimum activity occurred in 1977 with only eight TCs which is compared with a maximum of 24 cases in 1992 (Lawrence and Rappaport 1994).

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During the above seasons, there were 96 landfall counts in the west coast of Mexico (Fig. 1). The majority of them were in BCS (32) and in Sinaloa (21). This implies that nearly half of the landfalling TCs had direct impact in a limited portion of the northwest.

Additionally, Fig. 2 indicates that a maximum of six cases made landfall during the season of 1981 (Gunther 1982). Between one and three TCs moved across BCS and further examination of their temporal distribution reveals that they tend to occur in late August, the entire month of September or early in October (see upper-right insert in Fig. 1). In contrast, there were no landfalls at all during 16 seasons that include the periods 1978-1980 and 1985-1988.

Figure 3 shows groups derived from a classification of TC tracks with respect to an arbitrary site located at 25.4°N, 111.6°W. The first group represents 32 systems that crossed the southern peninsula (Fig. 3a). The other groups made no landfall in BCS but they developed within 400 km (Fig. 3b), in the range of 400-800 km (Fig. 3c), and in the range of 800-1200 km (Fig. 3d) from the arbitrary site. As expected, the heaviest rainfall episodes occurred during landfalling events and another important group are the non-landfalling tracks within 400 km. The tracks moving near or south of Isla Socorro (Fig. 3c and 3d) provide limited contribution to the rainfall accumulations collected by the rain-gauge network in BCS.

Figure 4 shows the temporal evolution of monthly rainfall (mm) at selected stations. They are located along a nearly southeast-northwest direction (Fig. 1). An examination of the corresponding time series results in the following set of results:

- There is a tendency for monthly maxima to occur in Cabo San Lucas and minima in Diaz Ordaz, which suggests a northward decrease of the tropical cyclone influence. This is consistent with the results published by Englehart and Douglas (2001).
- At Cabo San Lucas, most maxima is during the month of September (35%), October (22%), and August (15%).
- Many of the maxima are related to the approach or landfall of TCs sometime during the respective month. However, there are some exceptions where the maxima occurred without TCs close to the area.

In order to provide a broader perspective, the rain gauge dataset is used to determine long-term (1970-2009) annual means as well as monthly and daily maxima as shown in Table 1. Recall that station locations are in Fig. 1.

Table 1. Rainfall parameters (mm) for selected stations in Baja California Sur

Station number	Annual mean	Monthly max (month/year)	Daily max (month/day/year)
❶	246	437 (Sep/01)	257 (Sep/01/98)
❷	182	298 (Sep/76)	137 (Sep/30/76)
❸	163	374 (Sep/97)	319 (Sep/23/97)
❹	114	200 (Dec/94)	119 (Dec/05/94)

This table suggests that:

- Annual means depend on latitude with the largest amount (246 mm) at Cabo San Lucas.
- Loreto had a significant event that resulted in the largest daily maximum (319 mm) on 23 September 1997, which doubles the annual mean.
- Maxima at Diaz Ordaz, in the central peninsula, are dominated by a weather system from the cool season of 1994.

Based on the information from Table 1 and Fig. 4, we proceed to make a brief review of specific cases that provided significant rainfall to the selected stations.

3.1 Hurricane Juliette (2001)

In a unique case, the slow motion of TC Juliette brought accumulations that exceeded 750 mm during the period 26-29 September. The largest accumulations, up to 1011 mm (e.g., Farfán 2004), were south of 24°N while the circulation center passed 100-200 km from the west coast as a category 3 hurricane. At Cabo San Lucas, Juliette supplied 396 mm that corresponds to 91% and 80% of the September and annual accumulation in 2001, respectively. Earlier in this season, other TCs provided some rainfall such as Flossie (21 mm) in August and Ivo (35 mm) in mid September.

3.2 Hurricane Nora (1997)

It is important to discuss the likely source of rainfall for the 23 September maximum in Loreto, which is the largest record from the table. Best-track records indicate that the event is associated with the development of Nora 300-400 km west of the station, as a category 2 hurricane. Inspection of satellite imagery (GOES-9, not shown) reveals the development of a Mesoscale Convective System (MCS) in the eastern peninsula and over the Gulf of California. The interaction of humid flow, from Nora's leading edge, with the mountains seems to be an important source of intense convection and precipitation around the station. Previous research (Farfán 2005) documents a case study of convective outbreaks, in BCS, while a tropical storm was weakening several hundred kilometers away from Cabo San Lucas.

3.3 Hurricane John (2006)

Strong TCs tend to make landfall over the southeastern peninsula. Among this group, John (2006) arrived as a category-2 hurricane and remained over land for more than 40 hours to provide 265 mm in Loreto. Daily rates from John set new records at several stations throughout the state and maximum rates were in the range of 270-450 mm d^{-1}. Most of these stations were located within 50-100 km from the circulation center and were subjected to flash-flooding conditions.

Previous maxima (< 425 mm d^{-1}) were associated with the passage of only six TCs: Liza (1976), Lester (1992), Isis (1998), Juliette (2001), Ignacio (2003), and Marty (2003). In fact, the Cabo San Lucas daily maximum (257 mm d^{-1}) comes from Isis and the one from La Paz (137 mm d^{-1}) originates from Liza. Most of these TCs followed tracks with strong meridional component of motion. In contrast, only Liza did not make landfall in BCS and belongs to group 2 in the track classification shown in Fig. 3.

3.4 Other rainfall sources

No landfall occurred from 1978-1980 or 1985-1988, which is consistent with a period of lower accumulations (≤100 mm/month) in Fig. 4. As expected, annual accumulations from the selected sites were under the long-term means. These years were examined individually and likely sources of rainfall were identified to be:

- TCs moving close to the coast (group 2 in Fig. 4) or passing within few hundred km away from the peninsular landmass (group 3)
- MCSs that developed over the Gulf of California or over the peninsula or,
- weather systems typical of the cool season of the year.

In addition, the examination reveals that MCS development serves a secondary source of rainfall over BCS. Some of these MCSs initiate over the Sierra Madre Occidental, cross the gulf, and eventually reach the southern peninsula. In addition, there is subset of MCS that developed over limited areas (50-100 km) and short time scales (1-3 hours). These systems tend to originate over the peninsular mountains, remain almost stationary during their lifecycle, and provide accumulations below 50 mm.

More landfall events does not necessarily imply more rainfall in BCS. For example, in both 1984 and 2008, three TCs moved over land. However, rainfall accumulations were not always above the normal. This is because the landfall areas were affected by mostly weakening tropical storms or tropical depressions moving into the west (Pacific) coast. This fact indicates the importance of TC intensity and size as well as location of the strike area with respect to the spatial distribution of stations.

4. Conclusion

This study documented the impact, over southern Baja California, from tropical weather systems during the period 1970-2009. These systems include TCs from the eastern North Pacific basin and MCSs that initiate over land. A total of 608 named TCs developed and 32 (5%) of them made landfall over the west coast of Mexico.

Data from a regional network of rain gauges are used to determine spatial coverage and intensity patterns. The largest contribution to the rainfall received in BCS is from relatively intense TCs (hurricanes) with slow forward motion. In a matter of few days, one of these events (Juliette 2001) resulted in up to 90% of the annual budget at Cabo San Lucas. Other TCs, that moved along the peninsula, were responsible of record daily rates and the presence of flash-flooding conditions over the high terrain.

Tracks were classified into three additional groups according to their closest approach to the peninsula (Fig. 3). One important group is that from TCs that moved close (< 400 km) to the coast such as Liza (1976) which resulted in maximum monthly and daily rates at La Paz. Tracks moving near or south of Isla Socorro provided limited contribution to the rainfall accumulations collected by the SMN network in BCS.

These results are from ongoing research and future work involves identification of physical mechanisms that lead to the development of the above heavy rainfall episodes. This requires examination of in situ data and fields from regional-scale analyses.

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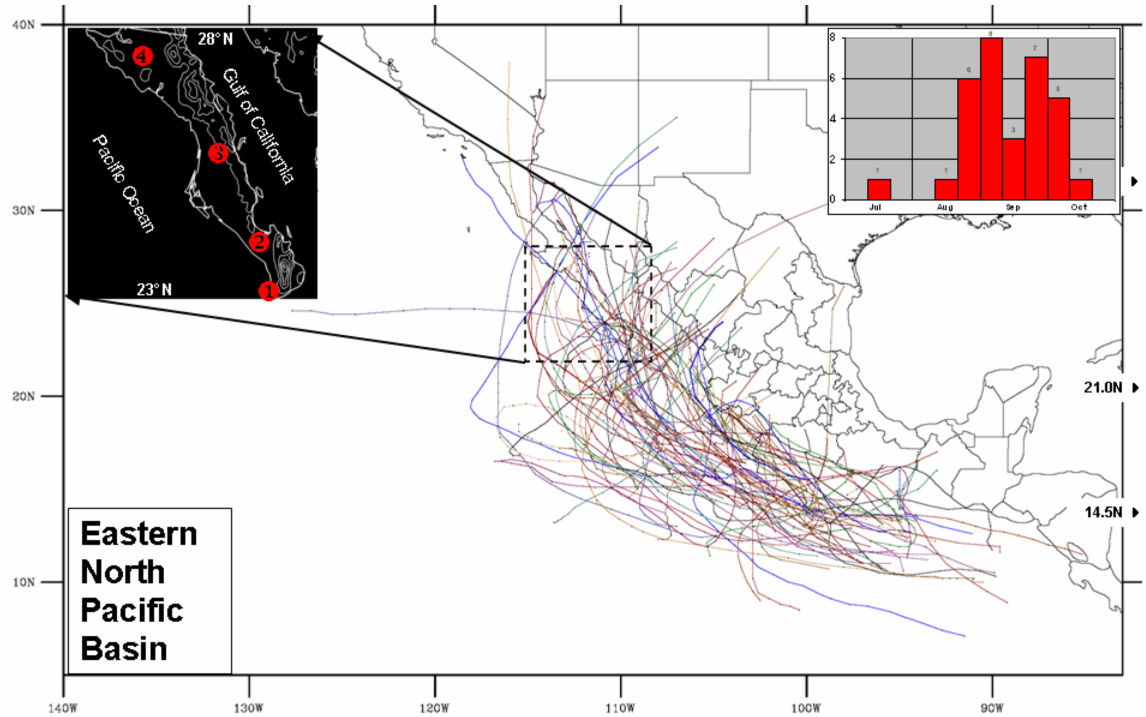

Figure 1. Tracks of 96 tropical cyclones that made landfall in western Mexico during the period 1970-2009. The upper-left insert shows selected sites in the southern Baja California Peninsula (1:Cabo San Lucas, 2:La Paz, 3:Loreto, and 4:Diaz Ordaz). Terrain elevations are indicated with contour intervals of 300 m. Landfall frequency in the southern peninsula, for 10- or 11-day periods, is indicated in the upper-right insert.

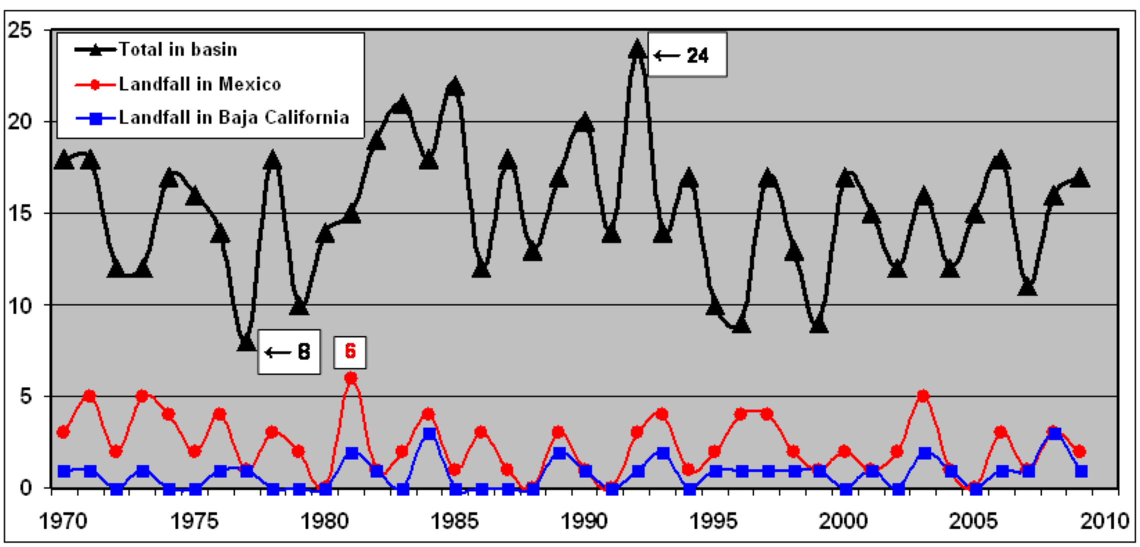

Figure 2. Time series of tropical cyclone frequency in the eastern North Pacific basin during the period 1970-2009. Total frequency in the basin (black line, triangles) and landfall in the west coast of Mexico (red line, circles) and in the peninsula (blue line, boxes) are indicated. Boxed numbers indicate relevant records discussed in the text.

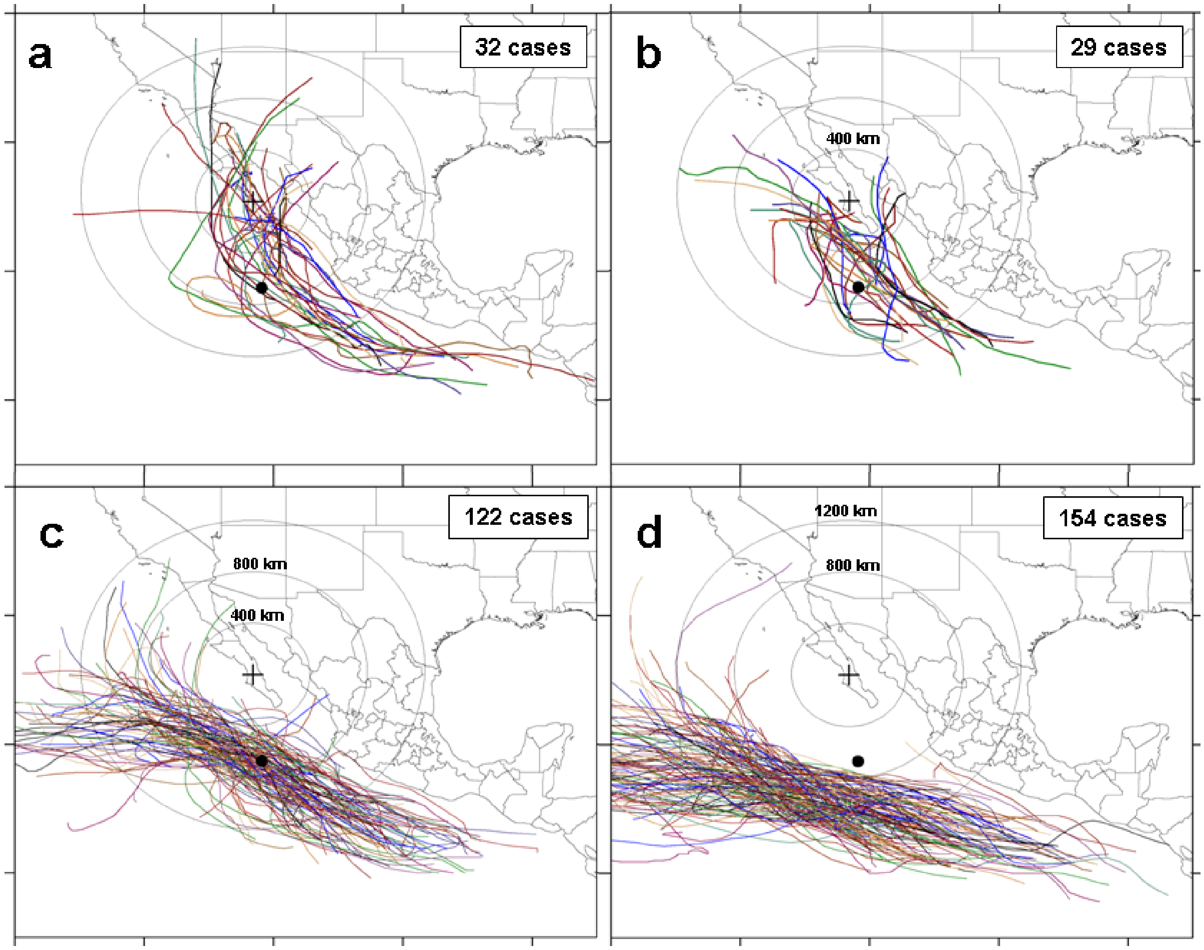

Figure 3. Tracks of tropical cyclones that made landfall in Baja California Sur (a) and tropical cyclones that moved within 400 km (b), 400-800 km (c) and 800-1200 km from the plus sign located at 25.4°N, 11.6°W. The black dot represents Isla Socorro.

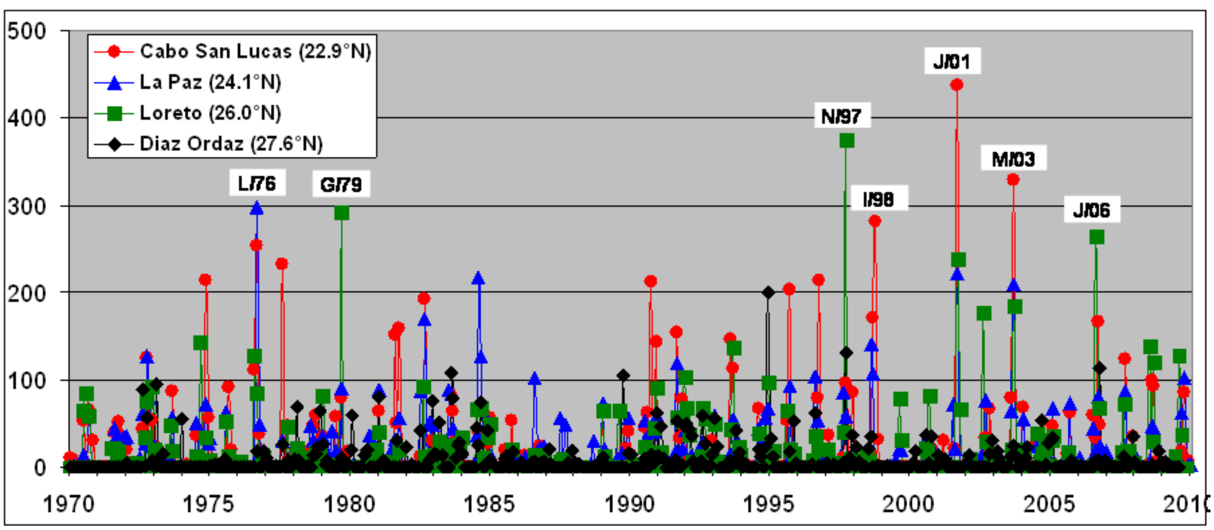

Figure 4. Time series of monthly rainfall (mm) at selected stations in Baja California Sur from 1970 through 2009. For accumulations above 250 mm/month, labels indicate the name initial and two-digit year of tropical cyclones approaching or making landfall in the southern peninsula.