Influence of Tropical Cyclones on Humidity Patterns over Southern Baja California, Mexico

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ABSTRACT

The influence of tropical cyclone circulations in the distribution of humidity and convection over northwestern Mexico is investigated by analyzing circulations that developed in the eastern Pacific Ocean from 1 July to 21 September 2004. Documented cases having some impact over the Baja California Peninsula include Tropical Storm Blas (13–15 July), Hurricane Frank (23–25 August), Hurricane Howard (2–6 September), and Hurricane Javier (15–20 September). Datasets are derived from geostationary satellite imagery, upper-air and surface station observations, as well as an analysis from an operational model. Emphasis is given to circulations that moved within 800 km of the southern part of the peninsula. The distribution of precipitable water is used to identify distinct peaks during the approach of these circulations and deep convection that occurred for periods of several days over the southern peninsula and Gulf of California. Hurricane Howard is associated with a significant amount of precipitation, while Hurricane Javier made landfall across the central peninsula with a limited impact on the population in the area. An examination of the large-scale environment suggests that advection of humid air from the equatorial Pacific is an important element in sustaining tropical cyclones and convection off the coast of western Mexico.

1. Introduction

There were 12 named tropical cyclones in the eastern Pacific Ocean from late May through October 2004 (Avila et al. 2006), with 9 events occurring between July and September. Most of these systems remained at sea. Late in the summer Tropical Cyclone Javier made landfall as a depression, moved across the Baja California Peninsula on 19 September, and reached mainland Mexico the next day. In contrast 15 systems developed in the North Atlantic, but none made landfall along the Gulf of Mexico or Caribbean Sea coasts of Mexico (Franklin et al. 2006).

This study analyzes humidity and convection during the approach of tropical cyclones to Baja California in the eastern Pacific basin. This basin encompasses the area north of the equator from the west coasts of Central and North America westward to 140°W. Tropical cyclone activity serves as a source of humid air masses that provide conditions that support deep convection over northwestern Mexico, including the Baja California Peninsula. These conditions tend to occur throughout the summer, with the most favorable locations over the southern peninsula. This pattern is associated with increased cloud cover followed by organized convective systems that may result in heavy precipitation (Farfán 2005).

Figure 1 shows the frequency of named storms from 1990 to 2004, information derived from the best-track dataset available at the U.S. National Hurricane Center (NHC). The 219 storms during this 15-yr period yield a mean of 14.6 storms per season. This is slightly lower than the mean of 15.5 during the study period of 1971–2003 (Levinson 2005). Minimum activity occurred in 1996 and 1999, with 9 tropical cyclones per season, contrasted with 24 cases in 1992. Figure 1 also indicates landfall events in western Mexico. The darker bars indicate that from zero to four cases made landfall each year, of which one or sometimes two cases, moved across the Baja California Peninsula.
Tracks of two tropical cyclones that developed during the 15-yr period are shown in Fig. 2. The circles are used as a reference of distance of the storm circulation with respect to the southern peninsula (centered at 25.4°N, 111.6°W). Hurricane Juliette (2001), associated with heavy precipitation and strong winds, is representative of landfall events with a strong impact on the southern part of the peninsula. Juliette had a relatively long track that started beyond the 1200-km radius, off the southeastern coast of Mexico, and made landfall on the western side of the peninsula (Farfán 2004). As shown in Fig. 2, the system moved across the peninsula and northward over the Gulf of California, weakening over the following few days.

In contrast to the impact from systems making direct landfall, the passage of tropical cyclones with northwest tracks also provides rainfall. Accumulation of rainfall seems to be directly proportional to the distance of the storm center (Englehart and Douglas 2001) from the impacted area, making these tropical cyclones a complementary and essential source of rainfall. For example, while located 400–500 km southwest of Cabo San Lucas, Tropical Cyclone Linda (2003; see Fig. 2) brought convective outbreaks on two consecutive days (Farfán 2005). Satellite and in situ data indicate that a large-scale mass of moist air from the storm’s eastern flank was advected into the southern peninsula and gulf.

This study focused on tropical cyclones that had a significant impact on the Baja California Peninsula during the 2004 storm season and documents the regional and large-scale conditions present during the development of these storms. This is an important season to examine, in part, because several systems moved close to the southern part of the peninsula (22.9°–28.0°N) and one of them, with a track similar to that from Juliette (2001), made landfall there. The specific objectives are as follows:

- based on the distance from the southern peninsula and best-track positions, classify the development of tropical cyclones that occurred between July and September 2004,
- evaluate the vertical and horizontal structures of humidity to provide documentation on the development of convection and rainfall associated with the closest approach of these tropical cyclones, and
- describe the impact caused by the landfall of Hurricane Javier from observations recorded by the regional network of surface stations.

This paper is divided into six sections. Section 2 describes the data sources. Best-track information and the evolution of humidity are described in section 3. Characteristics of the regional and large-scale environments for selected storms are discussed in sections 4 and 5.
respectively. Section 6 provides the summary and concluding remarks.

2. Data sources

The best-track dataset of tropical cyclones in the eastern Pacific, compiled by the NHC, provides a record of the position of the center of circulation every 6 h (Avila et al. 2006). The dataset includes categories of intensity: tropical depressions (sustained wind < 17 m s$^{-1}$), tropical storms (sustained wind > 17 m s$^{-1}$), and hurricanes (sustained wind > 33 m s$^{-1}$). Our analysis covers the storm events from 1 July to 21 September 2004.

Upper-air soundings were examined to identify large-scale characteristics of the atmospheric environment over northwestern Mexico, the southwestern United States, and the adjacent oceanic areas. These data include regular (1200 UTC) releases and special soundings taken for the North American Monsoon Experiment (NAME), which is intended to improve predictions of warm season precipitation over North America (Higgins et al. 2006). During the 2004 field season, soundings were taken twice daily (1200 and 0000 UTC) for stations in northwestern Mexico and the southwestern United States. During intensive observing periods (IOPs), soundings were taken at intervals of 4–6 h over several consecutive days.

Digital imagery from the Geostationary Operational Environmental Satellite-10 (GOES-10) provides patterns of the mid- to upper-level humidity and the structure of the cloud cover. This includes images of the water vapor and infrared channels at resolutions of 8 and 4 km, respectively. Additional information on the three-dimensional structure of large-scale flow is supplied by the gridded analyses of the Global Forecast System (GFS) model. This model is operated by the U.S. National Centers for Environmental Prediction (NCEP), and analyses are available at a grid resolution of 100 km $\times$ 100 km.
To determine patterns and the intensity of significant rainfall events, data from the Mexican network of rain gauges managed by Comisión Nacional del Agua (CNA) was used. These records are available as 24-h totals ending at 1500 UTC (local time is $-6$ h). In southern Baja California, most of the stations are located at elevations below 500 m, a limiting factor for assessing rainfall in the mountain ranges. Rainfall records from regional airports were provided by Servicios a la Navegación en el Espacio Aéreo Mexicano (SENAEM) and automated stations operated by Servicio Meteorológico Nacional (SMN) are also used.

3. Storm tracks and airmass characteristics

a. Best-track data

Figures 3 and 4 show the tracks of the eight tropical cyclones that occurred during the storm season of 2004. A summary of their structure and intensity is provided in Table 1. This table includes data from the best track at the time each system had its closest approach to Baja California. The radius of $17 \text{ m s}^{-1}$ wind speed is used as an estimate of circulation size.

In general, storm systems moved westward or northwestern toward the central Pacific, and each cyclone remained active for 4–11 days. The closest approaches to the peninsula by storms that did not make landfall occurred with Blas, Frank, and Howard. Track centers were within 800 km of the coast for at least 1 day. Hurricane Javier, which made landfall, was also included in this group. Three tropical depressions (Beven et al. 2005; see their Fig. 2) were too far beyond (1200–2100 km) the area of direct influence and were not evaluated.

Direct influence refers to storm centers that passed within the 800-km-radius circle for more than 24 h. Distant influence refers to storm centers that passed within
the 800-km radius for 24 h or stayed outside this circle. Tropical Cyclones Celia, Darby, and Isis were categorized as having a distant influence on Baja California, so they were not included in this study. Tropical Storm Georgette remained in the above circle for only 24 h (Table 1) and Estelle (19–24 August, not shown) crossed the western boundary of the eastern Pacific basin during its early stages of development.

The partition of tracks used in this analysis resembles one used by Higgins and Shi (2005) in the study of moisture surges in the Gulf of California. For the period of 1979–2001, they found that the intensity of surges is influenced by the proximity of tropical cyclones to the landmass. Storms that have a “direct influence” on surges were associated with tracks close to the gulf, which resulted in higher humidity at lower levels and heavy precipitation over northwestern Mexico. In contrast, tropical cyclones with tracks too far from the gulf resulted in a limited increase in humidity and rainfall. Figure 2 shows the mean positions for direct-influence and indirect-influence tracks included in that study.

Tracks of the first tropical cyclones of 2004 started south of the peninsula between the 800- and 1200-km circles (Fig. 3). Four of the subsequent storms started off the southern coast of Mexico, east of 111.5°W (Fig. 4). Most storm systems reached their maximum intensity in the vicinity of Isla Socorro, located 475 km south of the tip of the Baja Peninsula (Fig. 2), and weakened when their paths moved north of 20°N. This is related to the continued presence of the cold California Current and strong vertical shear of horizontal winds from west-northwest of the island (see Hobgood 2003). Javier was the only storm that moved north of the island and made landfall on the peninsula (Fig. 4). Its track was similar to that of Hurricane Juliette (2001; see Fig. 2), including the features of 1) initial development off southern Mexico, 2) passage through the area be-
T he tropical cyclones during the 2004 season in the eastern Pacific.

<table>
<thead>
<tr>
<th>Storm</th>
<th>Date</th>
<th>DIST</th>
<th>VMAX</th>
<th>R17W</th>
<th>NH8K</th>
</tr>
</thead>
<tbody>
<tr>
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<td>14 Jul</td>
<td>627</td>
<td>19</td>
<td>185</td>
<td>42</td>
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<tr>
<td>Celia</td>
<td>19 Jul</td>
<td>1251</td>
<td>15</td>
<td>111</td>
<td>0</td>
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<tr>
<td>Darby</td>
<td>26 Jul</td>
<td>1472</td>
<td>18</td>
<td>129</td>
<td>0</td>
</tr>
<tr>
<td>Frank</td>
<td>24 Aug</td>
<td>641</td>
<td>32</td>
<td>139</td>
<td>72</td>
</tr>
<tr>
<td>Georgette</td>
<td>27 Aug</td>
<td>778</td>
<td>26</td>
<td>102</td>
<td>24</td>
</tr>
<tr>
<td>Howard</td>
<td>4 Sep</td>
<td>646</td>
<td>31</td>
<td>194</td>
<td>105</td>
</tr>
<tr>
<td>Isis</td>
<td>9 Sep</td>
<td>940</td>
<td>21</td>
<td>143</td>
<td>0</td>
</tr>
<tr>
<td>Javier</td>
<td>17 Sep</td>
<td>434</td>
<td>50</td>
<td>185</td>
<td>150</td>
</tr>
</tbody>
</table>

| Table 1. Selected parameters from structure and intensity of tropical cyclones during the 2004 season in the eastern Pacific. |

Date = day and month associated with best-track data at 1200 UTC.  
DIST = distance (km) from center of circulation to 25.4°N and 111.6°W.  
VMAX = maximum sustained wind speed (m s⁻¹).  
R17W = radius of 17 m s⁻¹ isotach in the northeastern quadrant.  
NH8K = number of hours within the 800-km-radius circle.

between Isla Socorro (19°N) and Cabo San Lucas (23°N), and 3) eastward deflection of the track north of 25°N.

b. Precipitable water and rainfall

Figure 5 shows the amount of precipitable water estimated by the 1200 UTC upper-air soundings taken at La Paz (24.1°N, 110.3°W; see Fig. 2 for location), close to the Gulf of California. Morning releases are used to avoid convective activity, occurring later in the day, which distorts the correct operation of the humidity sensor. Precipitable water, below the 39-mm average (dotted line), occurred more frequently during the early study period, in the range of 15–35 mm. Values above 40 mm are evident during the times when the tropical cyclone tracks are within the area of direct influence (≤800 km).

Precipitable water remained at or below average during the development of distant-influence storms: Celia, Darby, and Isis. Their great distance from the Baja California Peninsula (≥940 km; Table 1), small circulation size (≤143 km), and weak intensity (≤21 m s⁻¹) help to explain a reduced contribution of moist-air advection onto the peninsula. In contrast, several peaks in precipitable water occurred in response to other sources of moisture, such as mesoscale convective systems (MCSs) that originated over the Mexican mainland. The MCSs moved across the gulf overnight, eventually raising the moisture content over the peninsula. While our focus is on the influence of topical cyclones without regard to the role of MCSs, we recognize that this is an important meteorological feature to be considered in future studies.

Precipitable water measured at other stations in

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northwestern Mexico (not shown) provides data that conditions prevailing in the coastal region of La Paz were drier than along the coast of mainland Mexico. For example, at the same time, Mazatlán (23.2°N, 106.4°W) and Guaymas (27.9°N, 110.8°W) had precipitable water averages of 52 and 42 mm, respectively. Satellite imagery supports sounding data that more favorable conditions for deep convection are present on the coastal plains and western foothills of the Sierra Madre Occidental of the mainland. A recent study by Gochis et al. (2004) used a rain gauge network to document that the center of summer precipitation is located just northwest of Mazatlán.

The heavy solid line in Fig. 5 displays the percentage of precipitation equal or above 10 mm that was measured by the network of 110 rain gauges in the southern peninsula. This provides a simple comparison between daily rainfall with respect to precipitable water and the passage of tropical cyclones. Where the line touches the zero mark, very limited or no rainfall was reported by the stations. In contrast, on 4 and 5 September (days 66 and 67), maxima of 56% and 50% of stations recording accumulations above the 10-mm threshold, respectively, occurred. These peaks occurred with the approach of Howard and were preceded by several days with precipitable water above the 39-mm average. In contrast, Javier’s passage did not generate values above the average for more than 24 h and accumulations above the threshold remained under 25% after 18 September (day 80).

c. Vertical structures

Time series of horizontal winds and mixing ratio are shown in Fig. 6. This type of display has been used to examine the passage of moist air masses over a particular station (Adang and Gall 1989; see their Fig. 4). Our data are derived from regular and special soundings at La Paz for five to six consecutive days. The profiles are used to study vertical structures within the atmospheric flow during the passage of Blas (Fig. 6a), Frank (Fig. 6b), Howard (Fig. 6c), and Javier (Fig. 6d).

Estimates of precipitable water from soundings prior to the approach of Blas were in the 28–32-mm range (Fig. 5). During the approach of the storm and the next few days, enhanced moisture (>40 mm) occurred in La Paz. As part of the NAME field activities, the second IOP was launched and sounding intervals were reduced to 4 h from 12 to 15 July (Higgins et al. 2006). On 13 July, the increased frequency of soundings helped identify the arrival of a well-defined layer (750–400 mb) of southeasterly winds (Fig. 6a). At 1630 UTC on 13 July, maximum speeds from a surface station at Cabo San Lucas were 21.3 m s$^{-1}$ (not shown). While the storm center was moving inside the 800-km circle, the surface mixing ratio rose to 15 g kg$^{-1}$ and values greater than 10 g kg$^{-1}$ extended above 850 mb. At 1200 UTC 14 July, the radius of circulation was 185 km (Table 1), while estimates of size during the previous 24 h ranged from 330 to 370-km. Therefore, Hurricane Blas had a relatively large horizontal coverage.

The percentage of substantial rainfall reached a peak of 6.5% of the network on 14 and 15 July (Fig. 5), the maximum during the first 55 days of the study. On 15 July, the center of Blas moved outside the direct-influence area and southeasterly flow weakened, while acquiring components from the west and north the next day (Fig. 6a). Precipitable water in La Paz and daily precipitation measured by the network declined.

Hurricane Frank entered the area in late August and brought air with enhanced moisture. The evolution of the mixing ratio is shown in Fig. 6b. A distinct layer of humid air (>15 g kg$^{-1}$) was present near the surface during the 1200 UTC releases. Table 1 shows that, while Frank had stronger intensity and smaller size than Blas, both systems resulted in comparable humidity profiles at the sampling station (Figs. 5 and 6b).

The impact of subsequent storms is illustrated in Fig. 6c (Howard) and Fig. 6d (Javier). For Howard, the humid layer (mixing ratio 15–20 g kg$^{-1}$) was present below the 925-mb level from 1 to 7 September. For this tropical cyclone season, the maximum network rainfall occurred on 4–5 September (days 66–67; Fig. 5) when Howard was 600–700 km from the southern peninsula (Fig. 4) and had a relatively large circulation size (194 km in Table 1). In contrast, the approach and eventual landfall of Hurricane Javier occurred within an environment of limited moisture and dry air (<10 g kg$^{-1}$) within the 700–925-mb layer. These data came from upper-air soundings, which were increased to every 6 h in the NAME’s 10th and last IOP on 17–20 September (Higgins et al. 2006).

4. Regional-scale environment

The observations discussed above indicate that the approach of tropical cyclones brings increased humidity to the southern part of the peninsula. In this section, we provide a description of the spatial characteristics of flow, humidity, convection, and precipitation. This includes conditions associated with four tropical cyclones when they were within the direct-influence area: Blas (Fig. 7), Frank (Fig. 8), Howard (Fig. 9), and Javier (Fig. 10). Figures display data derived from GOES-10 imagery, GFS analyses, and rainfall from CNA stations.
a. Tropical Storm Blas (13–15 July)

Figure 7a shows water vapor imagery and estimates of precipitable water from the regional network of soundings at 1200 UTC 14 July. The storm center is about 700 km west of Cabo San Lucas and humid conditions (precipitable water >45 mm) were present over the peninsula, gulf, and as far north as Arizona. Data from the NAME station at Loreto (26.0°N, 111.3°W) and the Research Vessel Altair in the southern gulf (23.5°N, 108.0°W) are incorporated into the figure.

Low-level fields from the GFS analysis (Fig. 7b) were used to identify the structure of the cyclonic circulation extending across the southern part of the peninsula. The relative vorticity maximum (not shown) is consistent with the position of the best-track center. The circulation is associated with a horizontal gradient of the mixing ratio, which has a maximum (>17.5 g kg⁻¹) occurring southeast of the storm center. Southeasterly flow is present along the gulf and provides advection of moist air concentrated south of 26.0°N. These conditions are consistent with the development of a moisture surge over the gulf (Higgins and Shi 2005).

In a composite image of deep convection, the pattern of cloud tops is shown in Fig. 7c. This image displays minimum temperature (maximum cloud tops) and is
derived from hourly, infrared imagery from 1200 UTC 13 July to 0000 UTC 16 July, when Blas was inside the direct-influence area (see Fig. 3). The image lacks deep convection off the California coast and, during most of the period, on the western flank of the storm. On 13 July, temperatures below $-60^\circ$C occurred east of the storm center, near the southern part of the peninsula, and, at the end of the period, over the central part of the peninsula. Precipitation data collected by the rain gauge network (Fig. 7d) showed scattered areas of light rain along both flanks of the mountain ranges and the largest amounts (30–50 mm) near 27°N, 112.5°W.
Hurricane Frank (23–26 August)

On 21–22 August, a midlevel anticyclone, centered over the northern Gulf of Mexico (not shown) dominated conditions present during the early stages of Tropical Cyclone Frank. Frank entered the direct-influence area on 23 August, intensified into a hurricane, and reached maximum intensity early on 24 August (see Fig. 3). At 1200 UTC 24 August (Fig. 8a), the storm center was 300 km northwest of Isla Socorro. Frank’s eastern flank did not trigger strong surface winds and the maximum speed measured at Cabo San Lucas remained under 10 ms⁻¹ (not shown). This agrees with the light winds at low levels (Fig. 6b), as
well as a weak and poorly defined circulation pattern (Fig. 8b).

La Paz had two consecutive days with precipitable water above 45 mm (days 56 and 57; Fig. 5). However, a dry air mass was centered north of Guaymas, related to an upper-level anticyclonic system over the southwestern United States. Animation of the satellite imagery shows eastward motion of the system from the Pacific coast of California into central Arizona, and the 850- and 200-mb analyses (not shown) indicated strong wind shear. This environment restricted Frank’s circulation to lower latitudes (20°–23°N) and its
movement into the central Pacific during the next few days.

Convective features during the 72 h ending at 0000 UTC 27 August are shown in a composite image (Fig. 8c). A limited area of deep convection (below -60°C), associated with the storm center, was located southwest of Cabo San Lucas. Another area of maximum convection is over the southwestern Gulf of California during the storm’s closest approach to the peninsula. The convective maximum is consistent with the distribution of storm-related precipitation near 25°N (Fig. 8d). In contrast, stations north of 26°N received limited rainfall (0–2 mm), which is related to the dry air mass (Figs. 8a and 8b) and the absence of deep convection (Fig. 8c).
c. Hurricane Howard (3–6 September)

The approach of Howard is associated with persistent humid air and heavy precipitation during the first week of September (days 63–69; Fig. 5). Most of the storm track was south and west of the peninsula (Fig. 4). Of the five storm systems that entered the 800-km-radius circle (except Javier), Howard moved farthest north, to 27.5°N on 6 September. This storm remained inside the 800-km circle for more than 4 days (105 h; Table 1).

Higher humidity covered most of the southern part of the peninsula and a large portion of the southern Gulf of California (Figs. 9a and 9b). Measurements of dewpoint at airports on both coasts of the southern Gulf of California ranged from 23° to 27°C (mixing ratio of 17–23 g kg⁻¹) from 3 through 6 September. La Paz soundings had lifted indices that were marginally unstable (0° to −4°C); some convective available potential energy (25–700 J kg⁻¹) was evident from morning launches. The combination of these factors provided a favorable environment for afternoon convection. Since airflow over the mountain ranges had a large southerly component (Fig. 6c), mean motion of convective systems was toward the central Gulf of California and Mexico’s mainland (Fig. 9c). In the southern peninsula, about 50% of the rain gauge network received daily accumulations above 50 mm, mostly at sites south of 27°N (Fig. 9d). For comparison, while accumulations were up to 200 mm per station, this amount was equivalent to only 20% of the recorded maximum during the approach of Hurricane Juliette (2001; Farfán 2004).

Low-level winds (Fig. 9b) indicate that advection of moist air in the northeastern quadrant of cyclonic circulation may be a significant element in keeping humidity above the average. The huge area of maximum humidity (mixing ratio >17.5 g kg⁻¹) extended south to the ITCZ (~10°N). Further discussion of this feature is provided in section 5.

d. Hurricane Javier (16–19 September)

With the exception of Tropical Depression 16–E in late October, Javier was the only system making landfall on the Pacific coast of Mexico in 2004. While centered about 540 km southeast of Isla Socorro, Javier became the strongest hurricane of the season, reaching a maximum wind speed of 67 m s⁻¹ (Fig. 4). The hurricane entered the direct-influence area on 15 September, steered by midlevel, southeasterly airflow associated with an anticyclonic circulation centered over the Gulf of Mexico (Fig. 12c). Eastward deflection to the peninsula resulted in Javier’s landfall on 19 September near 26.6°N (asterisk in Fig. 10d). Neither property damage nor casualties were reported (Avila 2004).

At 1200 UTC 17 September, mid- to upper-level moisture was concentrated over the southern part of the peninsula and adjacent gulf, while a dry-air environment covered the southwestern United States (Fig. 10a). Below average precipitable water was estimated at Guaymas (37 mm) and La Paz (34 mm), with reduced humidity at low and middle levels (Fig. 6d). When the tropical cyclone center was 250 km southwest of Cabo San Lucas (Fig. 10b), advection of dry air from the Pacific covered its western flank. The lack of deep convection west of 114°W is shown in the composite of infrared images (Fig. 10c). A few rain gauge stations around the landfall area reported total accumulations above 50 mm (Fig. 10d), but most of the stations outside this area had limited (<25 mm) accumulations.

The evolution of winds and humidity at three stations on the peninsula is depicted in Fig. 11. Ciudad Constitución and Gustavo Díaz Ordaz are not coastal (Fig. 10d). There were no sustained winds (10-min average) with speeds of tropical storm or hurricane intensity, which clarified why there were no reports of even limited property damage. Cabo San Lucas (Fig. 11a) recorded speeds from 5 to 15 m s⁻¹ and high humidity (mixing ratio >20 g kg⁻¹). The interaction of Javier’s circulation with the environment over the Pacific Ocean resulted in less humid air at Ciudad Constitución (15–20 g kg⁻¹; Fig. 11b), where southeasterly winds had maximum speeds in the northeastern quadrant of the tropical depression. As the circulation approached Gustavo Díaz Ordaz, a southwesterly to northwesterly wind shift occurred (by 0000 UTC 20 September) and dry air (<15 g kg⁻¹) was present after the center moved across the station (Fig. 11c). This situation suggests the entrainment of cool and dry air from the Pacific, which is consistent with the weakening intensity seen in the best-track records.

5. Large-scale environment

Large-scale environmental flow is known to strongly modulate the track, intensity, and structure of a tropical cyclone (Daida and Barnes 2003). Based on this framework, we performed further analysis of the environment during the development of Tropical Cyclones Howard and Javier. These systems remained in the direct-influence area for more than 4 days (Table 1), but resulted in different amounts of precipitation (Fig. 9d and 10d). Figure 12 shows fields at the 500-mb and surface levels from GFS analyses over the eastern Pacific, North America, and Gulf of Mexico. Precipitable water and the 2-m mixing ratio are given as an aid to identify relevant areas of humid and dry air during the approach of the storms to the Baja California Penin-
Fig. 11. Time series from automated surface observations at (a) Cabo San Lucas for 1200 UTC 16 Sep–1200 UTC 18 Sep, (b) Ciudad Constitución for 1800 UTC 17 Sep–1800 UTC 19 Sep, and (c) Gustavo Díaz Ordaz 1200 UTC 18 Sep–1200 UTC 20 Sep 2004. Sustained wind speeds (m s$^{-1}$, left axis) and mixing ratio (g kg$^{-1}$, right axis) are indicated with thick and thin lines, respectively. Wind barbs use same notation as in Fig. 6 and caret symbol (^) marks the time of the closest approach of the best-track center.
An outstanding feature is the ITCZ, an area of maximum humidity along 10°N, where intense convective activity is demonstrated in the satellite imagery.

According to best-track positions from Fig. 4, Howard moved with a prominent meridional component during most of its cycle. This was associated with steering flow from an anticyclonic system centered over the Gulf of Mexico and a wave trough over the western United States (Fig. 12a). The configuration results in high precipitable water (>50 mm) and moderate (>10 m s⁻¹) southerly winds along the 105°–115°W meridional band. Corresponding surface fields (Fig. 12b) have an extensive band of moist air, with a mixing ratio above 17.5 g kg⁻¹ to the north of the equator and west of the Pacific coast. Winds near the surface (10 m) show intrusion of flow from the equatorial Pacific (0°–10°N) and a cross section along 110°W (not shown) indicated the considerable vertical extent of the southerly flow (up to the 300-mb level) over the southern part of the gulf and peninsula.
The distribution of humid air during the movement of Hurricane Javier was different. Limited flow from the equatorial Pacific provided less precipitable water to northwestern Mexico (Fig. 12c). Winds south of Javier’s core have a westerly component, entraining dry air from the Pacific, related to a smaller area of humid air (precipitable water >50 mm) around the storm core. There is a wave trough off the western United States, but it is too far away to influence Javier. Additionally, surface analysis (Fig. 12d) indicates that the cross-equatorial flow was diverted and directed toward the west coast of Central America. The structure of this westerly flow is also captured by the National Aeronautics and Space Administration’s (NASA) Quick Scatterometer (QuikSCAT, not shown); therefore, it is almost certain that this feature occurred at the surface level.

GFS analyses suggest that part of the surface level, humid flow into the storm’s circulation and northwestern Mexico originates from the equatorial Pacific. Inspection of the corresponding fields for Blas indicated southerly flow east of the core (Fig. 7b) and scattered areas of convection over the southern part of the peninsula (Fig. 7c). In contrast, weaker southerly flow (Fig. 8b) and reduced storm size (Table 1) are associated with less convection east of Frank’s core (Fig. 8c).

To our knowledge, the study by Reyes and Cadet (1988) was the first to document [from the First GARP (Global Atmospheric Research Program) Global Experiment dataset] the role of cross-equatorial flow in tropical cyclone environments. They concluded that the presence of weaker, southerly flow from the southern Pacific (along 100°W) provided less water vapor and low-level advection off western Mexico. This condition was associated with below normal activity of ten tropical cyclones during the season of 1979.

6. Summary and concluding remarks

The goal of this study was to document the influence of tropical cyclones on the vertical and horizontal patterns of humidity over the southern Baja California Peninsula (23°–28°N).

During the eastern Pacific season of 2004, activity was below the annual mean of 15; 9 systems developed between July and September. Based on the NHC best-track positions, four storms that approached the peninsula were selected for analysis: Tropical Storm Blas and Hurricanes Frank, Howard, and Javier. These systems entered the direct-influence area (800-km-radius circle) from an arbitrary point at 25.4°N, 111.6°W. Upper-air observations and GFS analyses were applied to identify significant changes in mid- to low-level moisture, and satellite imagery determined areas of convective activity during the passage of each storm.

Sections 3 and 4 described the development of selected tropical cyclones. Most of these storm systems, at their closest approach, passed at distances less than 650 km and spent more than 40 h inside the direct-influence area (Table 1). We showed that their development resulted in periods of above average (39 mm) precipitable water at La Paz, as well as a moderate-to-heavy precipitation over the southern mountain ranges of the peninsula. Enhanced humidity resulted from the advection of mid- to low-level moisture in the flow of the eastern flank of tropical cyclones. However, Javier showed limited impact because of environmental conditions that weakened the circulation during the approach and landfall over the west coast of the peninsula.

Key findings of the study are the following:

- Data collected from the field phase of the NAME project provided an improved set of upper-air observations in northwestern Mexico. Special soundings taken at La Paz were important for detecting episodes of higher humidity during the passage of tropical cyclones and for identifying the vertical extent of mixing ratio layers and the structure of the incident flow (Fig. 6).
- Tropical Storm Blas provided a well-defined period of enhanced humidity (Fig. 5), along with scattered areas of precipitation (Fig. 7); the impact of this system was associated with a relatively large area of the horizontal circulation.
- Of the four selected storms, Hurricane Frank had the smallest circulations and produced moderate impacts on the humidity fluctuations at La Paz, along with limited areas of deep convection and accumulated precipitation (Fig. 8).
- The eastern flank of the circulation of Hurricane Howard (Fig. 9) was associated with prominent convective activity. Moist air was advected into the southern part of the peninsula and Gulf of California, conditions that led to deep convection and high precipitation that were recorded by the regional network of rain gauges.
- Hurricane Javier (Fig. 10) made landfall in the central part of the peninsula, but had practically no impact upon the convective activity. Time series from automated stations (Fig. 11) were used to determine storm impact during its approach and overland passage. This included winds below tropical storm intensity and lower humidity after passage of the storm center.
- Examination of the large-scale environment (section 5) suggests that low-level advection of humid air from
the equatorial Pacific is an important element supporting the development of tropical cyclones with intense convective activity and rainfall off the coasts of northwestern Mexico. This is consistent with a study by Reyes and Cadet (1988). Midlatitude systems also play a role in controlling the behavior of storm tracks and the structure of humidity surrounding storm circulations.

There was a set of storms (Celia, Darby, and Isis) that developed within the study period, but their movement was too far from the peninsula and had negligible impact. Additionally, they were small and had weak circulation; this resulted in a very limited contribution to the advection of moist air.

A similar methodology to the one used in this study is being applied to tropical cyclone seasons from 1991 through 2003. The anticipated results will increase our knowledge of how regional environments affect approaching systems and provide a more general set of results to better understand the impacts of storms in the southern part of Baja California.

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