13D.4 **THE IMPACT OF TROPICAL CYCLONE REMNANTS ON THE RAINFALL OF THE NORTH AMERICAN SOUTHWEST REGION**

by

Elizabeth A. Ritchie[1*], Kimberly Wood[1], Sarah White[1], and David S. Gutzler[2]

[1]University of Arizona
[2]University of New Mexico

## 1. INTRODUCTION

The North American southwest region has a mild, arid or semiarid, continental climate characterized by low annual precipitation, abundant sunshine, low relative humidity, and a relatively large annual and diurnal temperature range. Summer rains fall almost entirely during brief, but frequently intense thunderstorms. In general, a southerly circulation from the Gulf of Mexico brings moisture into the region, and strong surface heating combined with orographic lifting as the air moves over higher terrain produce the thunderstorms. The location of the Gulf of Mexico high-pressure system is critically important for location of the monsoonal moisture and summer precipitation in the North American southwest. July, August, and September are the rainiest months, producing, on average, anywhere from 25 to 45 percent of the annual rainfall. There is a sharp west to east gradient in the NAMS precipitation from southern California to central Arizona with the long-term maximum extending from the Mexican border in eastern Arizona and New Mexico north through Colorado. However, in years when the location of the Bermuda high is shifted to the east, and the eastern Pacific subtropical high is stronger than normal, as little as 25-30% of the annual rainfall has fallen in these months.

An additional source of tropical moisture is occasionally advected into the Southwest U.S. from the Eastern Pacific and Gulf of Mexico in the form of tropical cyclone remnants. These mesoscale systems make landfall on the Mexican and Californian coastline and, if the synoptic conditions are favorable, advect over the North American southwest. Although the tropical cyclone-strength winds rapidly diminish upon making landfall, these systems still carry a large quantity of tropical moisture and, upon interaction with mountainous terrain, have the potential to drop copious amounts of precipitation. However, these systems are difficult to forecast accurately due to the nature of their interaction with the midlatitude flow.

Examination of the general circulation pattern of the Eastern North Pacific reveals a pattern that is dominated in the tropical regions by the inter-tropical convergence zone (ITCZ) and a midlatitude regime that is dominated by upper-level troughs. During June and July, these troughs generally remain well to the north, but as the Northern Hemisphere summer progresses from late summer into autumn, these troughs protrude farther south and interactions between these troughs and tropical cyclone remnants that are moving northward become more likely. Furthermore, tropical cyclone tracks in the eastern North Pacific tend to shift from westward, to more northwestward later in the season. Thus, the chance of interaction with midlatitude troughs increases as the season progresses. This is reflected in the histogram in Figure 1 with more TC remnants crossing into the U.S. southwest later in the season.

Tropical cyclones that move northward into the midlatitude regime go through a transition known as extratropical transition (ET). The ET of tropical cyclones is a common process in basins with tropical cyclones (e.g., Jones et al. 2003) and is complicated by the nonlinear interactions between the tropical cyclone and midlatitude circulations (e.g., Ritchie and Elsberry 2003; 2007). Forecasting of these systems is extremely difficult over the ocean because accurately predicting the interaction between the TC and midlatitude trough is dependent on an accurate prediction of both the propagation of the trough and the track acceleration as the TC moves into the midlatitude westerlies. In this case, an added difficulty of predicting overland effects is included because the precipitation

*Corresponding author address: Department of Atmospheric Sciences, PO Box 210081, 1118 E 4th St University of Arizona, Tucson, AZ 85721-0081.

associated with these events is dependent, not only on the large-scale dynamics of the trough and TC, but also on very localized orographic effects. We would like to identify characteristic patterns associated with these TC remnants as a forecaster aid to predicting track and rainfall associated with TC remnants that move into the desert southwest region.

This study is part of the North American Monsoon Experiment (NAME) (Gutzler et al. 2004), which is investigating predictability of warm season precipitation in the North American Monsoon (NAM). In this study we will investigate the impact that tropical cyclone remnants from the Eastern Pacific have on precipitation in the arid North American southwest region. We will study their climatological impact, the preferred rainfall patterns, and the nature of the large-scale circulations that advect them across the southwest U.S. using both observational and model data. The data and methodology used in this study will be described in section 2, some climatological results will be presented in section 3, a description of the large-scale patterns associated with tropical cyclone remnants in the southwest U.S. will be presented in section 4, and a summary and conclusions will be provided in section 5.

## 2. DATA AND METHODOLOGY

Data used in this study include best track data from the National Hurricane Center (NHC), daily precipitation data for several National Weather Service (NWS) stations across the southwest, GOES infrared and water vapor imagery, unified US-Mexico daily gridded precipitation analyses from the national Center for Environmental Prediction (NCEP), and global analyses from the NCEP/NCAR (National Center for Atmospheric Research) reanalysis.

Cases of tropical cyclone remnants from 1992-2005 that cross into the southwest U.S. are identified using NHC best track data and infrared and water vapor imagery. The areal extent of the precipitation associated with each tropical cyclone remnant is subjectively extracted from the US-Mexico unified daily precipitation analyses and plotted. The cases are binned by region using the daily precipitation data from various NWS stations located across the southwest U.S. and by track type, and various statistics are compiled from these data.

NCEP/NCAR reanalyses are used to examine the large-scale patterns associated with each TC remnant. The cases are separated first into precipitating, and non-precipitating cases based on the rainfall amounts that fall in the southwest U.S. region. Each case is then examined for characteristic large-scale midlatitude patterns and the nature of the interaction between the TC remnants and the midlatitude flow. Based on both the rain swaths and the large-scale patterns, 5 groupings are identified.

## 3. CLIMATOLOGY

Figure 1 shows the number of TC remnants that crossed into the southwest U.S. from the Eastern North Pacific by month during the period 1992-2005. The occurrence of TC remnants are skewed to the latter part of the season relative to the total population of Eastern North Pacific tropical cyclones. This is related to the tendency for midlatitude upper-level troughs to dig deeper into the tropics later in the season.

Remnants of forty-three TCs crossed into the southwest region during the 14-y period of the study. Of these, thirty-four remnants brought precipitation to some part of the southwest U.S. and the remaining nine remnants had precipitation that was almost entirely restricted to Mexico, although cloud cover did advect over the southwest U.S. in the majority of these cases. On average, 3.1 TC remnants impact the southwest each year bringing between 0 and

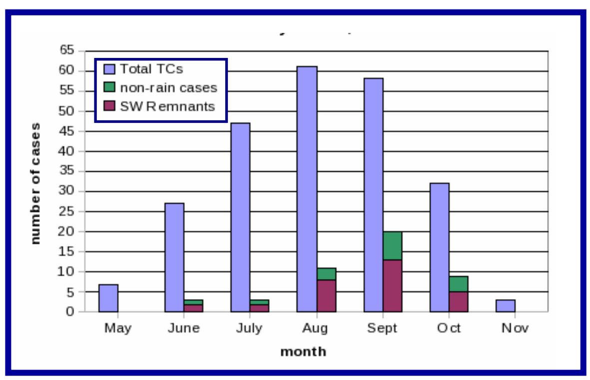


*Figure 1: Histogram of the number of tropical cyclone remnants that impacted the southwest U.S. region in the period 1992-2005 by month. Included in the histogram are TC remnants that produced rainfall and those that did not. Note that the TCs that did not produce rainfall in the U.S. all produced rainfall in Mexico.*

30% of the annual rainfall[1] to the region (depending on locality). The average number of days that were impacted annually by rainfall from remnants was 5.6 at Tucson, and 4.2 at Albuquerque.

## 4. RESULTS

Forty-three cases of TC remnants that crossed into or impacted the southwest region are examined for characteristic rainfall and large-scale patterns that can be exploited in aiding forecasters. We emphasize that there is considerable variability among the cases in terms of the spatial distribution of rainfall across the southwest. However, to aid in identifying patterns that will help discriminate this rainfall variability we begin by first broadly dividing the cases into characteristic remnant tracks and rainfall swaths. The large-scale patterns associated with the TC remnants in each broad category are then examined for common features that help to explain the shape of the rainfall swath. In particular, the presence and timing or absence of a midlatitude upper-level trough has a significant impact on the tracks of remnants. The groupings are subjective and open to some interpretation. We intend to apply some statistical methods to more robustly

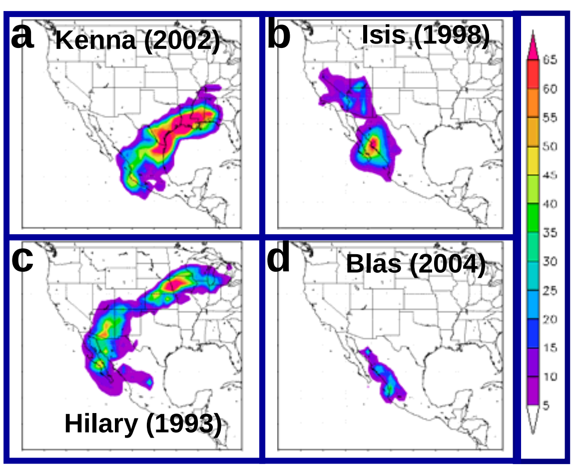


*Figure 2: Sample rainfall swaths for examples of each of the U.S. precipitating groupings: a) Group 1: Kenna October 24-28 2002; b) Group 2: Isis September 2-6 1998; c) Group 3: Hilary August 24-30 1993; and d) Group 4: Blas July 13-15 2004.*

separate the patterns. In our initial analysis, five groupings are identified based on the remnant tracks and rainfall swaths (Table 1). These groups include:

Group 1. NE movement only (Fig. 2a);
Group 2. N/NW movement only (Fig. 2b);
Group 3. N/NW to NE/E movement (Fig. 2c);
Group 4. No U.S. impact (Fig. 2d); and
Group 5. Special Cases.

We will discuss examples from Groups 1 - 4.

### *4.1 Group 1 – Kenna (2002)*

The "northeast-movement-only" group includes four of the forty-three cases (Table 1). It is characterized by a rain swath that begins on the Mexican west coast near (or on the tip of) the Baja Peninsula and extends across Mexico into Texas (Figure 2a). The remnant track is produced because the TC interacts with an upper-level midlatitude trough to the northwest

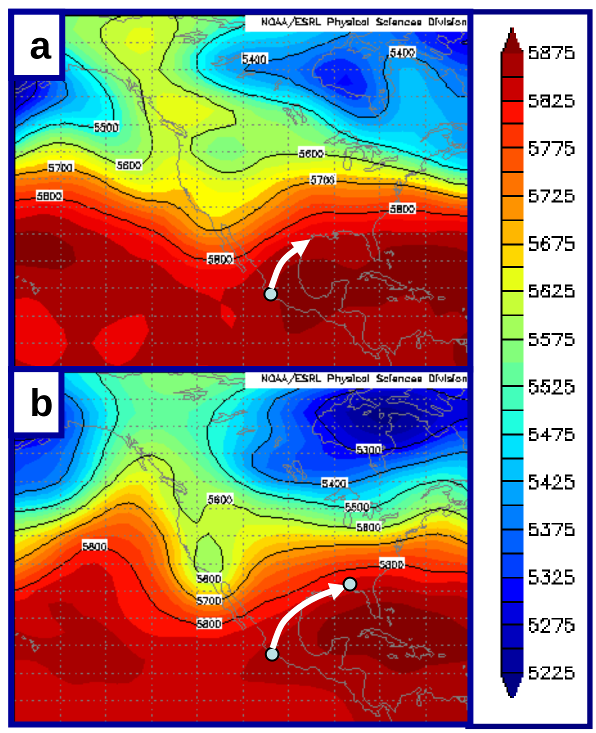


*Figure 3: Geopotential heights plotted at 500 hPa for Kenna (2002), at: a) 1200 UTC 25 October; and b) 1200 UTC 26 October. Note the low amplitude trough along the west coast of the U.S. The ridging downstream of the trough is very low amplitude, directing an advecting flow for the moisture out of Kenna along the Gulf Coast.*

[1] Figures are calculated at representative NWS sites for the southwest region including Phoenix International Airport, AZ, Tucson International Airport, AZ, and the Albuquerque Sunport, NM

that has relatively low amplitude and relatively little downstream ridging associated with it (Figure 3a). The remnants (this example is Kenna 2002) are advected to the ENE across Mexico and along the Gulf coast (Figure 3). Additional moisture is picked up from the Gulf of Mexico resulting in large amounts of precipitation in all cases.

### *4.2 Group 2 – Isis (1998)*

The "north/northwest movement only" group includes ten of the forty-three cases (Table 1). It is characterized by a rain swath that follows the Mexican west coast to the northwest and sometimes turns northward by the time it reaches the U.S (Figure 2b). The large-scale pattern is dominated by a ridge in the midlatitudes, well north of the tropical cyclone (Figure 4). The tropical cyclone propagates north and northwest (in the case of Isis) until it is finally picked up well north of the southwest U.S. region by an eastward moving upper-level trough. The preferred rainfall swath for this grouping extends northwest along California and Nevada, sometimes extending as far east as western Arizona. Total rainfall amounts tend to be less than for group 1.

### *4.3 Group 3 – Hilary (1993)*

The "northwest/north to northeast/east movement" group includes eleven of the forty-three cases (Table 1). It is characterized by a rain swath that follows the west coast of Mexico to the northwest and then turns to the northeast near the U.S.-Mexico border (Figure 2c). The large-scale pattern is dominated at early times in

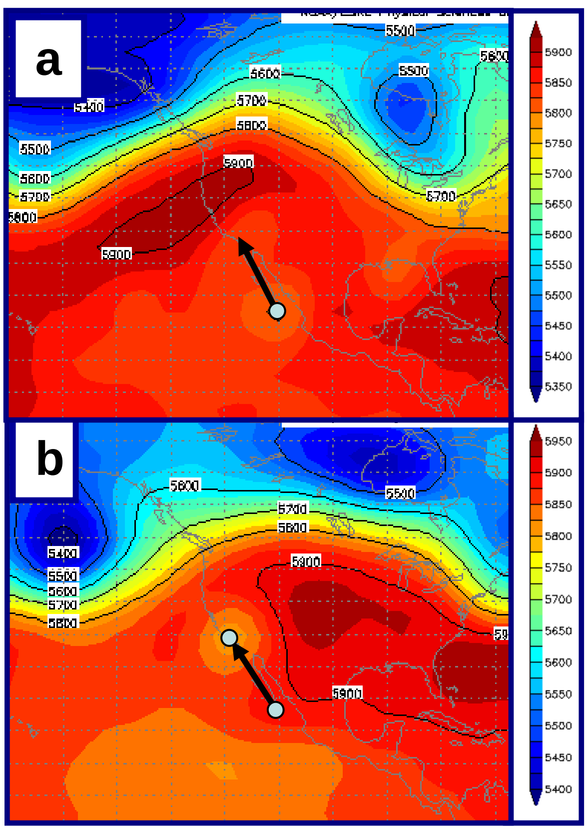


*Figure 4: Geopotential heights plotted at 500 hPa for Isis (1998), at: a) 1200 UTC 2 September; and b) 1200 UTC 5 September. The TC remnant on the tip of Baja in a) moves up the west coast of California in b). Subsequent to this figure a midlatitude trough approaches the west coast of the U.S. and the TC finally recurves in the midlatitudes well north of the U.S. southwest region.*

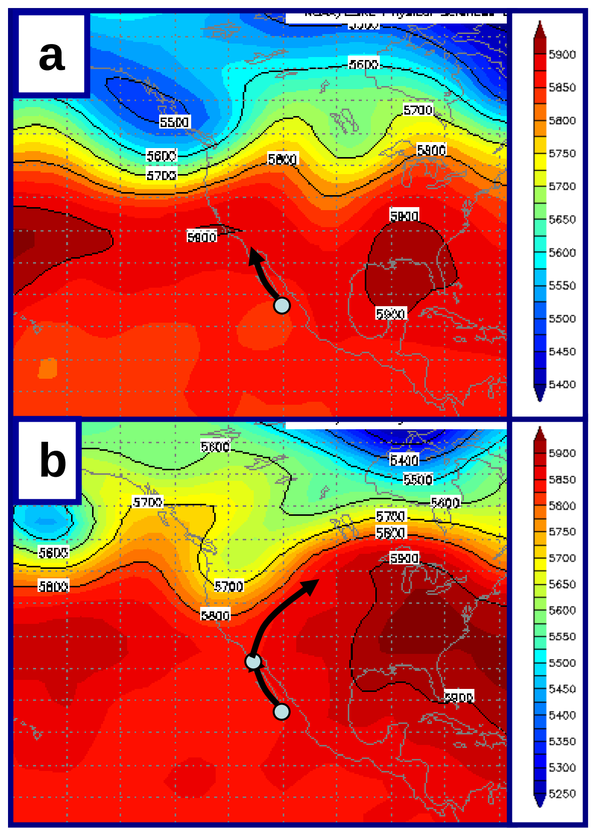


*Figure 5: Geopotential heights plotted at 500 hPa for Hilary (1993), at: a) 1200 UTC 23 August; and b) 1200 UTC 25 August. The TC remnant initially moves to the northwest under the influence of a weak ridge. As the midlatitude trough approaches the west coast of the U.S., the TC track recurves to the northeast and classic extratropical transition occurs.*

the sequence by a midlatitude ridge, similar to that for group 2 (Figure 5a). Later, as the TC moves north toward the U.S. an upper-level trough approaches the west coast. The TC recurves toward the northeast and east under the influence of the midlatitude trough (Figure 5b) and the resulting rain swath can extend across much of the continental U.S (Figure 2c). Total rainfall amounts are only slightly less than those for group 1.

### *4.4 Group 4 – Blas (2004)*

The "no U.S. impact" group includes nine of the forty-three cases (Table 1). It is characterized by a rain swath that moves north or northwest along the west coast of Mexico (Fig. 2d). The large-scale pattern is dominated by a westward-building subtropical ridge (Fig. 6), which tends to propagate the tropical cyclone to the northwest and west. The TC finally dissipates over colder sea surface temperatures and the resulting rain

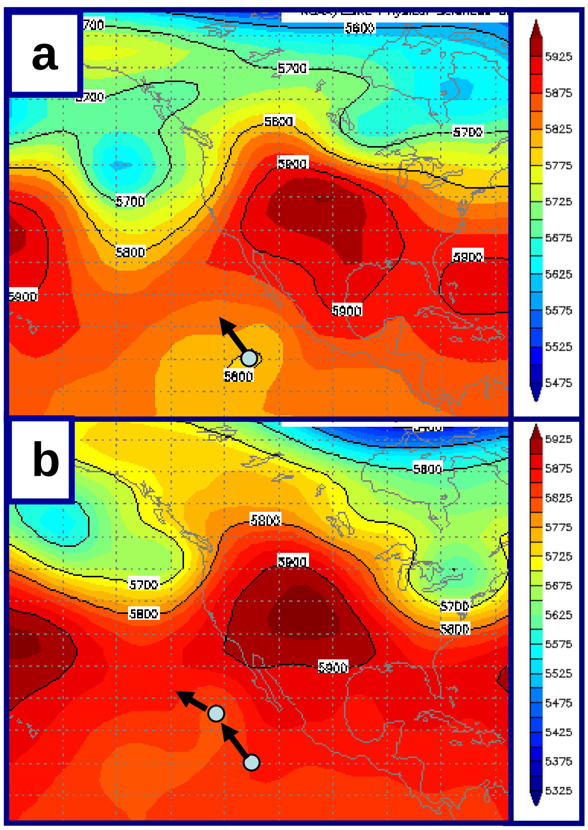


*Figure 6: Geopotential heights plotted at 500 hPa for Blas (2004), at: a) 1200 UTC 13 July; and b) 1200 UTC 15 July. The TC remnant moves to the northwest and west under the influence of a westward-building ridge. Eventually the TC moves away from the coast and dissipates over colder SSTs.*

swath is limited in extent generally to the Mexican west coast.

### *4.5 Group 5 – Special Cases*

This category is the catch-all for nine cases that do not fit into the first four groups. This category contains unusual cases including a TC that split into two with one rain swath going up the west coast of California, and the other tracking to the northeast over New Mexico and Texas (not shown).

## 6. DISCUSSION AND SUMMARY

Forty-three eastern North Pacific tropical cyclone remnants that affected the U.S. southwest region during 1992-2005 were investigated. On average 3.1 remnants impacted the region annually during the 14-y period. Out of forty-three cases, thirty-four brought rainfall to the southwest U.S. and the majority of the remaining nine brought cloud cover.

The cases were investigated for common large-scale circulation and rainfall patterns. Four main patterns were identified: northeast movement (9%), north/northwest movement only (23%) north/northwest then northeast/east movement (26%), and no U.S. rainfall (21%). Nine of the TC cases currently are not included in these categories (21%). The rainfall swaths for each TC remnant case were extracted from the 1 degree US-Mexico unified precipitation dataset. The remnant tracks and rainfall swaths were modulated by particular large-scale circulation patterns, which made it possible to characterize the flows associated with each expected rainfall swath. There can be considerable variability in the rainfall amounts at different locations along each swath, due in part, to differences in topography. However, the expectation is that we will be able to predict, with some confidence, the gross characteristics of the rainfall swath – its extent and track - based on the expected timing and interaction between the large-scale circulation and the TC remnants.

Future work includes increasing and updating the dataset. Currently 1988-1991 and 2006-2007 are being added. In addition, we would like to improve on our subjective characterization of the large-scale flow and rainfall patterns using some statistical methods to more robustly separate the patterns. A final task is to run a series of simulations forced by the observed large-scale flows in order to

| | TC Name | Dates |
|---|---|---|
| **Group 1** | 1993 Lidia | Sep 11-14 |
| **(4)** | 1996 Hernan | Oct 3-5 |
| | 1998 Madeline | Oct 16-20 |
| | 2002 Kenna | Oct 24-28 |
| **Group 2** | 1993 Calvin | Jul 7-10 |
| **(10)** | 1997 Nora | Aug 23-26 |
| | 1998 Isis | Sep 2-6 |
| | 1999 Hilary | Sep 20-24 |
| | 2000 Carlotta | Jun 23-27 |
| | 2001 Flossie | Auf 27-Sep 2 |
| | 2001 Ivo | Sep 13-14 |
| | 2001 Juliette | Seo 23-Oct 4 |
| | 2002 Hernan | Sep 7-8 |
| | 2004 Javier | Sep 16-20 |
| **Group 3** | 1992 Darby | Jul 6-9 |
| **(11)** | 1992 Lester | Aug 22-26 |
| | 1993 Hilary | Aug 24-30 |
| | 1994 Hector | Aug 7-11 |
| | 1995 Ismael | Sep 13-16 |
| | 1996 Fausto | Seo 12-17 |
| | 1998 Frank | Aug 7-10 |
| | 1999 Greg | Sep 8-13 |

| | TC Name | Dates |
|---|---|---|
| **Group 3** | 2003 Nora-Olaf | Oct 6-10 |
| | 2004 Howard | Sep 2-7 |
| **Group 4** | 1994 Ileana | Aug 12-13 |
| **(9)** | 1998 Javier | Sep 12-15 |
| | 2000 Ileana | Aug 14-15 |
| | 2000 Lane | Sep 11-15 |
| | 2000 Miriam | Sep 16-19 |
| | 2000 Norman | Sep 22-23 |
| | 2002 Genevieve | Aug 29-Sep 1 |
| | 2004 Blas | Jul 13-15 |
| | 2005 Otis | Sep 29-Oct 4 |
| **Group 5** | 1994 Rosa | Oct 12-17 |
| **(9)** | 1995 Flossie | Aug 11-12 |
| | 1997 Carlos | June 27-28 |
| | 1997 Ignacio | Aug 18-20 |
| | 1997 Olaf-Pauline | Oct 10-13 |
| | 2000 Bud | Jun 14-19 |
| | 2003 Ignacio | Aug 25-29 |
| | 2003 Marty | Sep 22-26 |

*Table 1: Groupings of tropical cyclones into common rainfall swath and track types.*

characterize the detailed rainfall patterns due to topography along each rainfall swath.

**Acknowledgments:** The analyses presented here were produced using the NOAA-CIRES/CDC reanalysis plotting page. This study has been supported, in part, by the National Oceanic and Atmospheric Administration under grant number NA030AR4310085.

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