P2.102 THE IMPACT OF EASTERN PACIFIC TROPICAL CYCLONES ON THE CLIMATOLOGY OF THE NORTH AMERICAN SOUTHWEST REGION

Kimberly M. Wood* and Elizabeth A. Ritchie
The University of Arizona

1. INTRODUCTION

The southwestern United States is a semi-arid region which receives much of its annual precipitation during the summer months, most of which is associated with the North American monsoon (NAM) (Adams and Comrie 1997; Higgins et al. 1997). Specifically, the states of Arizona, New Mexico, and Colorado get about half their yearly rainfall from July to September, on average, and most of this precipitation falls from thunderstorms generated by the moist, unstable atmospheric conditions associated with the NAM. However, there can be significant spatial and temporal variability in the amount of NAM rainfall occurring in the region both within a single season and from year to year (Adams and Comrie 1997).

An additional, irregular source of moisture for the southwestern U.S. during the NAM comes in the form of tropical cyclone (TC) remnants from the eastern North Pacific basin and the Gulf of Mexico (Corbosiero et al. 2009; Ritchie et al. 2010). Most of the TC remnants which enter the southwest U.S. from this basin are advected into the region due to interaction with a mid-latitude trough. Though the winds associated with these storms quickly weaken after landfall on the coastline of Mexico or, rarely, California, the tropical moisture they contain can produce large amounts of rainfall after interacting with local topography. However, many factors can change the behavior of this trough interaction and thus the resulting pattern and intensity of precipitation, posing an interesting forecast problem.

TCs moving northward into the mid-latitudes often undergo a process called extratropical transition (ET). ET, the process by which a TC's energy source shifts from latent heat release in a warm core to baroclinic processes with a cold core as it moves poleward into the mid-latitude flow, is a common occurrence in basins which produce TCs (Jones et al. 2003). However, ET is difficult to forecast due to its complex nature (Ritchie and Elsberry 2003; 2007) as well as the need to accurately predict both the rate of propagation of the trough and the TC track acceleration as it moves into the mid-latitude westerlies.

In order to better understand how TC remnants contribute to heavy precipitation events in the current climate, and eventually their role in a changing climate, this study focuses on analyzing large-scale patterns associated with TC remnants entering the southwestern U.S. Section 2 describes the data and methods used in this study, section 3 discusses the climatology of the eastern North Pacific basin, section 4 presents the results, and section 5 provides a summary and conclusions.

2. DATA AND METHODS

Best-track data from the National Hurricane Center (NHC) was used to track eastern Pacific TCs over the period 1992-2005 approaching the southwestern U.S. until the NHC ceased issuing advisories on each system. Further tracking was done using 3-hourly GOES visible and infrared satellite imagery until the TC remnant's moisture could no longer be identified. The tracks created for each system were then used to subjectively extract a corresponding rainfall swath using unified US-Mexico daily gridded precipitation analyses from the National Centers for Environmental Prediction (NCEP). These swaths were plotted and examined for overall emerging patterns.

Large-scale conditions for each TC remnant were examined using 6-hourly, 2.5-degree European Centre for Medium-range Weather Forecasts (ECMWF) 40-year Reanalysis (ERA-40) for cases in the period 1992-1999 and 6-hourly, 1-degree NCEP Final Analysis (FNL) data for cases in the period 1999-2005. 500 hPa geopotential heights, 500 and 200 hPa winds, and divergence calculated from 200 hPa winds were the main fields used. The composite analyses for each group focused on a turning point for each storm as well as two 24-hour intervals prior to and two 24-hour intervals subsequent to this turning point.

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

The cases in this 14-year period were first separated into rainfall and non-rainfall categories based on whether or not each TC contributed precipitation to the southwestern U.S. Each case was then examined using the fields outlined above for characteristic large-scale patterns and the way the TC interacted with the mid-latitude flow. Five groups were identified utilizing both the large-scale patterns and the precipitation swaths.

3. CLIMATOLOGY

Examining the general circulation in the eastern North Pacific shows that the tropical regions are dominated by the inter-tropical convergence zone (ITCZ) and the mid-latitudes by upper-level troughs. During June and July, these troughs generally remain well to the north, but as the season progresses from late summer into autumn, they protrude farther south. This increases the chance for an interaction between a troughs and a northward-moving TC remnant to occur. Also, TC tracks in the eastern North Pacific tend to shift from westward to more northwestward later in the season as the ridge in place over the southern U.S. and northern Mexico retreats eastward. Thus, the likelihood of TC interaction with mid-latitude troughs improves as the season progresses. This is reflected in the histogram in Figure 1 where more TC remnants enter the southwestern U.S. later in the season.

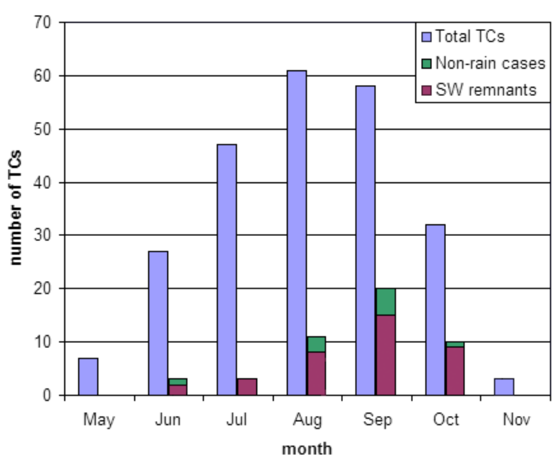

Figure 1. *Histogram of the number of TC remnants that impacted the southwestern U.S. during 1992-2005 by month. Note that the TCs that did not contribute rainfall to the U.S. all produced rainfall in Mexico.*

Forty-three TC remnants were identified as approaching or crossing into the southwestern U.S. over the period 1992-2005. Thirty-five of these remnants contributed precipitation to the southwestern U.S. The remaining eight remnants only contributed rainfall to Mexico, but in some of these cases cloud cover was advected over the southwestern U.S. The forty-three remnants identified were categorized into five groups, which will be discussed in the next section.

4. RESULTS

The large-scale and rainfall patterns associated with forty-three TC remnants that crossed into or impacted the southwestern U.S. region have been examined for characteristics that can be used to aid forecasters. We emphasize that there is considerable variability among the cases in terms of the spatial distribution of rainfall across the region. However, to aid in identifying patterns that will help discriminate this rainfall variability, we began 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 were 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. These initial groups will be presented first, followed by results from preliminary statistical analysis of the 1992-2005 cases. The TC remnants used in this study are listed in Table 1.

Out of the five groups identified over the forty-three cases, two of them consist of TC remnants which were advected into the southwestern U.S. due to interaction with a mid-latitude trough, or about half the cases investigated. Average rain swaths for these groups are shown in Figure 2.

Group 1 cases, usually occurring in August or September, experience ET farther north and are thus more likely to bring rain to the southwestern U.S. Eleven cases over the 14-year period comprise this group. An example of a group 1 TC is Hurricane Javier (2004) (not shown), which tracked largely parallel to the Mexican coastline before interacting with a westward-moving mid-latitude trough. The rapidly weakening TC turned northwestward and was brought over land due to the presence of this trough, and the tropical moisture associated with Javier's remnant contributed to measurable rainfall across much of the southwest, including 0.41” in Tucson, AZ.

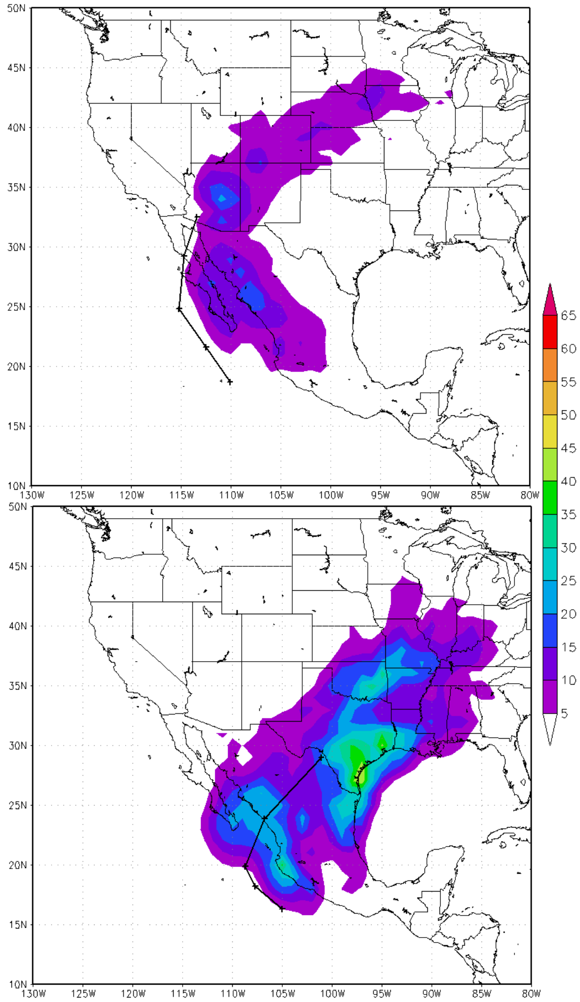

Figure 2. *Average rainfall swaths for ET groups: 1 (top) and 2 (bottom). Average 24h track from -48h to 48h superimposed.*

Group 2 cases, usually occurring in September or October, experience ET farther south and are thus less likely to bring rainfall to the majority of the southwestern U.S., but they tend to produce higher rainfall accumulations due to an average greater intensity prior to ET and an additional influx of moisture from the Gulf of Mexico as the remnants propagate eastward. Ten cases over the 14-year period comprise this group. Two pairs of cases were identified together in this group due to the difficulty subjectively distinguishing the moisture of one case from the moisture of another due to the close proximity of the TCs during their lifetimes. An example of a group 2 case is Hurricane Kenna (2002) (not shown), which continued to intensify after recurving to the northeast due to an upper-level trough and made landfall as a Category 4 hurricane. Its far-south recurvature and greater intensity at landfall, as well as the strength of the trough interacting with it, contributed to much greater rainfall occurring with this system compared with group 1 cases.

Cases in groups 3 and 4 differ from TC remnants in groups 1 and 2 due to the absence of a trough during most of their lifetimes. Instead, the relative strength of the ridge over the southern U.S. and northern Mexico has a large impact on the tracks of these TCs. The average rainfall swaths for these groups are shown in Figure 3.

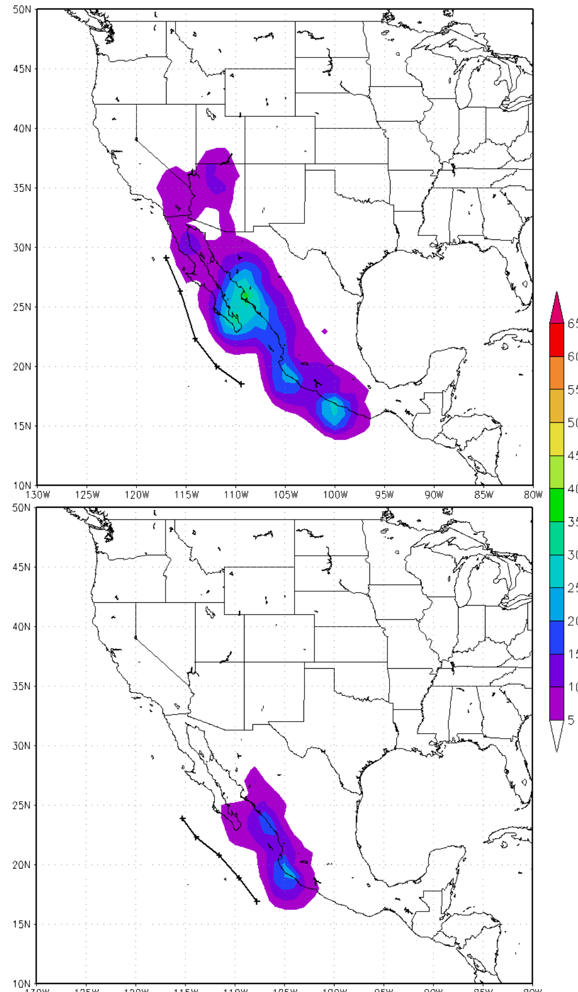

Figure 3. *Average rainfall swaths for groups 3 (top) and 4 (bottom). Average 24h track from -48h to 48h superimposed.*

Group 3 cases move northwest parallel to the Mexican coastline, occasionally turning north near the U.S., and their rainfall patterns follow this motion. However, these systems typically weaken rapidly as they move north of about 35° N, either because they are over land or because of the much cooler sea surface and low-level air temperatures. Thus, in most cases rainfall does not extend north or east beyond Arizona. The large-scale flow is generally characterized by a break in the ridge or a ridge retreating eastward. An example of a group 3 case is Hurricane Isis (1998) (not shown) which moved dominantly north before making landfall on the southern tip of Baja California. This TC moved north into a ridge over the western U.S., turning to the north-west after it made landfall. The remnant brought rain to western Mexico, Arizona, Cali-fornia, Nevada, and Utah. It was eventually captured by a mid-latitude low propagating eastward.

Group 4 cases do not bring rainfall to the south-western U.S. as they are usually blocked from the region by a mid-level ridge usually centered over Texas extending far westward over the Pacific Ocean. The flow associated with this ridge steers the TCs away from land and over cooler waters, where they dissipate. As a result, the average swath for these TCs parallels the western coast of Mexico but does not reach into the U.S. However, observations have been made of upper-level moisture from group 4 cases entering the southwest U.S. in the form of cloud cover, which can inhibit normal summer-time convection and thus rainfall in the region. An example of a group 4 TC is Hurricane Ileana (1994) (not shown) which initially moved parallel to the Mexican coastline before being steered westward by a strong ridge extending north and west of the TC. Measurable rainfall fell along western Mexico in association with the TC's passage, but it contributed no precipitation to the southwestern U.S. Some high-level clouds and moisture from the storm were advected into the region around the ridge, however, which may have inhibited normal summertime convection in some regions, such as Denver, CO (Figure 4). The potential for non-rain TC cases to instead prevent precipitation in the southwestern U.S. will be further investigated after the time period under study has been expanded to at least twenty years.

Group 5 cases do not fall into any of the previous four categories. Six of the forty-three TC remnants from 1992-2005 comprise this group. Many of them appear to have a forked or split precipitation swath, compared with the rela-tively linear progression of the swaths from the categorized cases. The large-scale pattern in place during the lifetime of these TCs is also abnormal compared with the patterns described earlier.

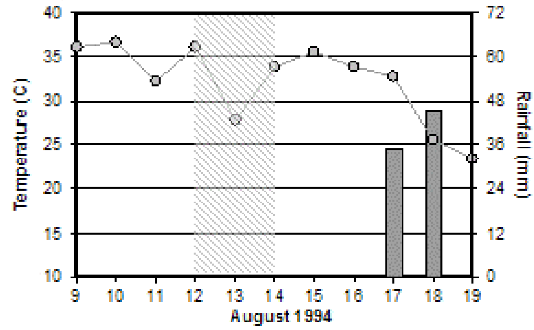

Figure 4. *Time series of temperature (°C) and precipitation (in.) for the Denver NWS station. Cross-hatched area denotes the time period for the passage of Ileana's moisture.*

An example of a group 5 case is Tropical Storm Ignacio (1997) (not shown) which underwent ET over open ocean as a weak TC and contributed to precipitation in both the southwestern and northwestern U.S. (Wood and Ritchie 2010).

These groupings were created based on subjec-tive analysis. Spatial pattern standard devia-tions were computed to determine how well representative the composite fields were of the individual TCs in each group (not shown), which showed that the standard deviations are fairly low up to 0h (the turning point time) and increase beyond that (Figure 5).

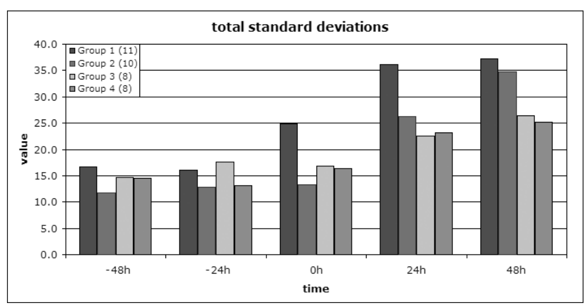

Figure 5. *Total standard deviations for 500 hPa geopotential height composites for groups 1-4.*

To objectively evaluate the robustness of the subjectively chosen groupings, EOF and REOF analysis was performed on the 500 hPa geopo-tential heights and rainfall swaths, respectively. This was done for the entire forty-three case data set as well as for two subgroups: the ET cases and the ridge cases. The first three 500 hPa EOFs (not shown) explained 46%, 21.8%, and 9.3% of the variance respectively. The first EOF showed a weakening ridge as a strong trough and/or TC approached, while the second EOF hinted at the potential role of cut-off lows as opposed to troughs in bringing some of these remnants into the region. The third EOF represented a weakened ridge and the lack of a trough interaction, representing the north-northwest moving cases. The REOFs for the rainfall analysis explained less variance and were less clear in delineating one type of case from another (not shown); this is largely due to the variance within each group's rainfall swaths as well as the differences between each group.

For comparison, the aforementioned subgroups were also analyzed. The first 500 hPa EOF for the 18-case ET sub-group is shown in Figure 6, where a stronger trough and weaker ridge are visible. This EOF mode explained 43.7% of the variance.

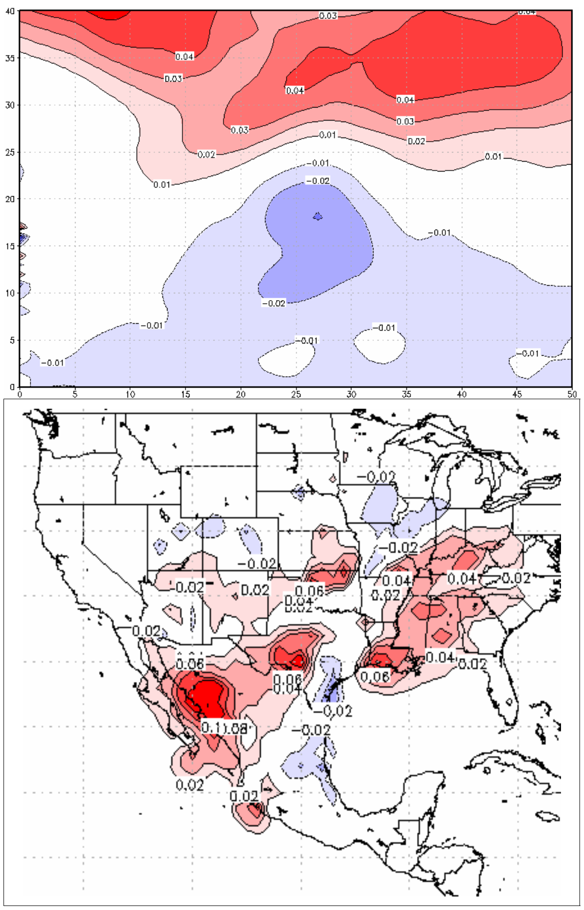

Figure 6. *500 hPa EOF1 (top) and rainfall swath REOF1 (bottom) for ET subgroup (18 cases).*

Figure 6 also shows the first REOF for the rainfall swaths in the ET subgroup. It explains only 20.5% of the variance, but it clearly demonstrates the variability in the spatial extent and amount of rainfall that can occur even within a carefully selected subgroup of cases. It also leans toward the southern ET type due to the greater amounts of rainfall and the more southerly extent of the given pattern. REOF2 (not shown) explained 19.3% of the variance, but it better emphasized the northern ET type compared with REOF1.

5. SUMMARY AND CONCLUSIONS

This study found forty-three eastern Pacific TC remnants impacting the southwestern U.S. over the 14-year period from 1992 to 2005. Four major patterns were observed from these TCs. The first group of 11 TCs underwent more northern ET and were more likely to contribute rainfall to the southwestern U.S. during August or September. The second group of 10 TCs underwent more southern ET and were less likely to contribute rainfall to the southwestern U.S., but these late-season TCs tend to produce more rainfall overall due to the combination of more intense systems and additional moisture from the Gulf of Mexico once they cross over Mexico and the south-central U.S. The third group of 8 TCs did not interact with a trough while near the southwestern U.S. but instead followed a more north or northwest motion pattern due to a weakened ridge in place over the southern U.S. and northern Mexico; this pattern tends to bring rain to the coastal and near-coastal western U.S. as the systems drift northward. 6 TCs did not fit into any of these groups, comprising the fifth group for the time being.

This study gave an initial analysis of dominant spatial patterns relating to TC remnants impacting the southwestern U.S. with the intent to aid forecasters. Expanding the data set to cover storms over at least 1990-2009 may change the categories from their current state as well as include TCs from group 5, thus improving the aid they can give to forecasters.

These groups were fairly consistent within each one as given by the spatial pattern standard deviations, but objective analysis was still needed to support those results. Preliminary findings from EOF and REOF analysis reinforces the subjective groupings outlined earlier, but spatial variability, even within a particular group type, must also be considered when examining these maps. Also, a larger data set will increase the sample size and improve these preliminary results. Once the data set is expanded, which is currently being done, the analyses outlined here will be repeated, and a correlation analysis between the 500 hPa geopotential heights and the rainfall swaths will also be performed.

Group 1 (11)	1992 Darby	Jul 6-9
	1992 Lester	Aug 22-26
	1993 Hilary	Aug 24-30
	1994 Hector	Aug 7-11
	1998 Frank	Aug 7-10
	1999 Greg	Sep 8-13
	2000 Carlotta	Jun 23-27
	2001 Ivo	Sep 13-14
	2004 Blas	Jul 13-15
	2004 Howard	Sep 2-7
	2004 Javier	Sep 16-20
Group 2 (10)	1993 Lidia	Sep 11-14
	1995 Ismael	Sep 13-16
	1996 Fausto	Sep 12-17
	1996 Hernan	Oct 3-5
	1997 Olaf-Pauline	Oct 10-13
	1998 Madeline	Oct 16-20
	2002 Kenna	Oct 24-28
	2003 Nora-Olaf	Oct 6-10
Group 3 (8)	1993 Calvin	Jul 7-10
	1997 Nora	Aug 23-26
	1998 Isis	Sep 2-6
	1999 Hilary	Sep 20-24
	2000 Lane	Sep 11-15
	2001 Flossie	Aug 27-Sep 2
	2001 Juliette	Sep 23-Oct 4
	2002 Hernan	Sep 7-8
Group 4 (8)	1994 Ileana	Aug 12-13
	1997 Carlos	June 27-28
	1998 Javier	Sep 12-15
	2000 Ileana	Aug 14-15
	2000 Miriam	Sep 16-19
	2000 Norman	Sep 22-23
	2002 Genevieve	Aug 29-Sep 1
	2005 Otis	Sep 29-Oct 4
Group 5 (6)	1994 Rosa	Oct 12-17
	1995 Flossie	Aug 11-12
	1997 Ignacio	Aug 18-20
	2000 Bud	Jun 14-19
	2003 Ignacio	Aug 25-29
	2003 Marty	Sep 22-26

Table 1. *Five TC remnant groupings according to large-scale patterns and rainfall swaths.*

6. REFERENCES

Adams, D. K., and A. C. Comrie, 1997: The North American monsoon. *Bull. Amer. Meteor. Soc.*, **78**, 2197–2213.

Corbosiero, K. L., M. J. Dickinson, and L. F. Bosart, 2009: The contribution of eastern North Pacific tropical cyclones to the rainfall climatology of the southwest United States. *Mon. Wea. Rev.*, **137**, 2415-2435.

Higgins, R. W., Y. Yao, and X. L. Wang, 1997: Influence of the North American monsoon system on the U.S. summer precipitation regime. *J. Climate*, **10**, 2600–2622.

Jones, S., P. Harr, J. Abraham, L. Bosart, P. Bowyer, J. Evans, D. Hanley, B. Hanstrum, R. Hart, F. Lalaurette, M. Sinclair, R. Smith, and C. Thorncroft, 2003: The extratropical transition of tropical cyclones: forecast challenges, current understanding, and future directions. *Wea. Forecasting*, **18**, 1052-1092.

Ritchie, E. A., and R. L. Elsberry, 2003: Simulations of the extratropical transition of tropical cyclones: contributions by the mid-latitude upper-level trough to re-intensification. *Mon. Wea. Rev.*, **131**, 2122-2128.

—, and —, 2007: Simulations of the extratropical transition of tropical cyclones: phasing between the upper-level trough and tropical cyclone. *Mon. Wea. Rev.*, **135**, 862-876.

—, K. M. Wood, D. S. Gutzler, and S. White, 2010: Eastern Pacific tropical cyclone remnants entering the southwestern U.S. *Submitted to Mon. Wea. Rev.*

Wood, K. M. and E. A. Ritchie, 2010: The unique behavior and precipitation pattern associated with Tropical Storm Ignacio (1997). *In prep. for Mon. Wea. Rev.*