Effects of Vertical Wind Shear on Tropical Cyclone Precipitation

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ABSTRACT

The response of the precipitation field for tropical cyclones in relation to the surrounding environmental vertical wind shear has been investigated using ~20 000 snapshots of passive-microwave satellite rain rates. Composites of mean rain rates, 95th percentile rain rates, and rain coverage were constructed to compare how the spatial distribution of the precipitation was organized under varying environmental shear. Results indicated that precipitation is displaced downshear and to the left (right for Southern Hemisphere) of the shear vector. The amplitude of this displacement increases with stronger shear. The majority of the asymmetry found in the mean rain rates is accounted for by the asymmetry in the occurrence of heavy rain. Although rain is common in all quadrants of the sheared tropical cyclones, heavy rain (≥8 mm h⁻¹ at the ~25-km scale) is comparatively rare in the upshear-right quadrant. It is shown that the effect that shear has on the rain field is nearly instantaneous. Strong westerly shear formed slightly more asymmetric patterns than strong easterly shear.

1. Introduction and background

Several studies have investigated the effects that vertical wind shear has on tropical cyclones (TCs) and their precipitation fields. The majority of these have been numerical model simulations (e.g., Jones 1995; Frank and Ritchie 1999, 2001; Rogers et al. 2003) or individual case studies (e.g., Black et al. 2002). A few exceptions are Lonfat et al. (2004), Chen et al. (2006), and Cecil (2007). This study aims to complement the previous studies by utilizing a robust sample set of satellite-derived rain rates to investigate the spatial effects TC precipitation encounters with respect to vertical wind shear.

a. Numerical studies

A series of modeling studies have shown mechanisms by which the downshear and downshear-left regions are favored for upward motion and precipitation. Dry, adiabatic simulations (e.g., Jones 1995; Frank and Ritchie 1999) identify two mechanisms for asymmetric vertical motion. First, the upper and lower portions of the vortex experience differential advection and the vortex tilts in response to the vertical wind shear. Mutual corotation of the upper and lower vortices causes the direction of tilt to rotate cyclonically from the shear vector. The direction of tilt is generally aligned a bit to the left of the shear vector. The potential vorticity advection induces a secondary circulation with adiabatic uplift in the downtilt direction (beneath the upper-level potential vorticity anomaly) in order to maintain balance. This uplift distorts the potential temperature field, and vortex flow along these distorted isentropes yields adiabatic uplift on the right side of the tilt vector.

In moist simulations (e.g., Frank and Ritchie 1999), latent heat release counteracts the adiabatic cooling and limits the second lifting mechanism (adiabatic uplift on the right side of the tilt vector). This leaves the secondary circulation associated with the potential vorticity anomaly forcing upward motion in the downtilt direction. Ueno (2008) noted that this vertical motion asymmetry introduces an asymmetry in the water vapor distribution, with the driest air to the upshear right as it exits the subsident region. This dry air does not saturate when initially lifted as it enters the downshear–downtilt region, and precipitation is instead displaced cyclonically (to the downshear-left region). This does not account for precipitation being carried cyclonically as it


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falls, which would further contribute to a left-of-shear precipitation enhancement.

Frank and Ritchie (2001) investigated how tropical cyclone intensity and structure are affected by environmental vertical wind shear magnitude. The strong shear (15 m s$^{-1}$) case began to weaken within 3 h while the weak shear case (5 m s$^{-1}$) did not weaken until $\sim$36 h. A clear wave-number-1 asymmetry (with maxima of rainfall and convection on the downshear-left side) did develop within a few hours for both the weak and strong shear cases, although this asymmetry did occur more rapidly for the 15 m s$^{-1}$ simulation. A similar asymmetry was noted in Rogers et al.'s (2003) simulation of Hurricane Bonnie (1998) during strong environmental shear, but the precipitation pattern quickly became symmetric when the shear relaxed. Ueno (2007) developed a formula relating the magnitude of the upward motion asymmetry to both the magnitude of the vertical shear and the intensity of the vortex.

Ritchie and Frank (2007) examined how planetary vorticity affects vertical wind shear in simulated tropical cyclones in the absence of environmental shear. Vertical wind shear was generally light and variable for the constant $f$ storm, but the variable $f$ storm developed significant vertical wind shear (850–200 hPa) ranging between 7 and 12 m s$^{-1}$. For both, the wind field below 400 hPa varied little. The majority of the change in shear was due to changes within the upper-level outflow region. Shear for the variable $f$ storm was consistently to the south-southeast or southeast. Such directions suggest that the shear developed from the advection of planetary vorticity will reduce (increase) southeasterly (northwesterly) environmental shear overall.

b. Observational composites

Corbosiero and Molinari (2002) used the National Lightning Detection Network (NLDN) to gather flash locations from 35 Atlantic tropical cyclones near the U.S. coast. Vertical wind shear (850–200 hPa) was computed using the European Centre for Medium-Range Weather Forecasts (ECMWF) analyses over a 500-km radius after a vortex removal method was applied. Within a radius of 300 km more than 90% of the flashes occurred in the downshear region of the storm. Within 100 km, there was a slight downshear left preference; however, between 100 and 300 km, this preference shifted to the downshear right. Observational constraints limited this study to tropical cyclones at relatively high latitudes and near land (i.e., near the United States).

Lonfat et al. (2004) was one of the first studies to incorporate a large sample set of passive-microwave-derived rain rates to investigate spatial distributions of rain in tropical cyclones. Using Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) data from 1998 to 2000, they were able to capture 260 individual storms resulting in 2121 instantaneous precipitation observations. The data was then put through a first-order Fourier decomposition to determine the asymmetry relative to the storm motion. Chen et al. (2006) used the same TMI dataset and methodology, but examined asymmetries relative to the 200–850-hPa environmental shear vector. The maximum relative asymmetry was found in the front quadrants relative to storm motion and shifted from the left to the right [in the Northern Hemisphere (NH); opposite in Southern Hemisphere (SH)] as intensity was increased from tropical storms to major hurricanes. The shape of the asymmetry did not alter for faster-moving TCs (>5 m s$^{-1}$), but the overall amplitude of the asymmetry did significantly increase. Relative to vertical wind shear, the rainfall asymmetry maximum occurs downshear left (right) in the NH (SH) and increases (decreases) with shear strength (TC intensity). The western North Pacific and South Pacific TCs were found to have the smallest asymmetry, while the Indian Ocean (both SH and NH) TCs had the largest.

Corbosiero and Molinari (2003) noted that the front-right quadrant favored by storm motion and the downshear-left quadrant favored by shear often overlap in their sample. By examining subsets where motion and shear favor opposing regions, they found that the effects of storm motion tend to be secondary to the effects of vertical shear when determining the relative asymmetry of the lightning flash locations. Similarly, Chen et al. (2006) and Ueno (2007) found that the downshear-left quadrant is favored for greater rain rates even when storm motion is in the opposite direction or right of shear. The magnitude of the asymmetry was greatest, though, when the shear vector and storm motion were oriented in the same direction or when storm motion was 90$^\circ$ to the left (right for SH) of the shear vector. Ueno (2007) pointed out that low-latitude western North Pacific vertical wind profiles tend to favor storm motion to the right of the shear vector, with motion to the left of the shear vector favored in midlatitudes (as in the Corbosiero and Molinari studies).

Cecil (2007) looked at how environmental vertical wind shear interacted with tropical cyclone rain rates in the Atlantic basin from 1988 to 2004. The rain-rate algorithm (Wentz and Spencer 1998) used for Cecil (2007) is the predecessor for the one used in this study. Vertical wind shear (200–850 hPa) was obtained from the Statistical Hurricane Intensity Prediction Scheme (SHIPS; DeMaria et al. 2005) developmental database. These initial results agreed with the previous observational and theoretical studies by showing that hurricane precipitation was enhanced in the downshear-left region of the storms. Tropical storms had much lower rain rates and
were displaced more downshear compared to downshear left for their hurricane counterparts.

The work presented here expands upon past studies in several ways: by extending the analysis to include other characteristics of the rain rates and vertical shear, refining the analysis techniques previously used, and expanding the database of satellite-derived rain rates. Specifically, the impact of vertical shear on different portions of the distribution of tropical cyclone rain rates, including both rain coverage and heavy rain coverage, is included. Also, preliminary comparisons of the impact of different layers of vertical shear are included here.

Several improvements to the techniques used in past studies are performed here. Whereas Lonfat et al. (2004), Chen et al. (2006), and Ueno (2007) discuss relative amplitudes of Fourier components; this study presents retrieved rain-rate values (mm h$^{-1}$) themselves. This study improves upon Cecil (2007) by using the Remote Sensing Systems (RSS) version 4 algorithm (Hilburn and Wentz 2008). The hurricane inner-core mean rain rates are over 50% lower for the new RSS algorithm than for the older algorithm used by Cecil (2007), and are between the mean values from TRMM standard products 2A12 and 2A25 (Cecil and Wingo 2009). Unlike in Cecil (2007), the shear is calculated from the 40-yr ECMWF Re-Analysis (ERA-40; Uppala et al. 2005) using a different approach (described in section 2). The rain rates are composited into octants instead of quadrants. More importantly, the rain-rate grid is rotated with respect to the shear vector before assigning the octants, providing greater accuracy when assigning location relative to the shear vector. Instead of just the Atlantic, this study branches out to include all active tropical cyclone basins, significantly expanding the sample size and allowing for comparisons of basins. SH shear-relative grids are flipped before compositing them with NH cases.

## 2. Data and methods

### a. Sample size

The 15 yr (1988–2002) of passive-microwave observations used for this study result in 20 028 instantaneous tropical storm and hurricane rain-rate retrievals from 1131 individual storms across all active tropical cyclone basins (Table 1). Of these, 6219 are hurricane coincidences comprising 620 individual hurricanes. The 1-min maximum wind was extracted from best-track data files obtained from the National Hurricane Center and the Joint Typhoon Warning Center. For this paper, hurricane is used to describe any tropical cyclone with winds greater than or equal to 64 kt (32 m s$^{-1}$), regardless of ocean basin. Tropical storms (maximum sustained winds between 17.5 and 31 m s$^{-1}$) have more than twice the sample size of hurricanes. The discrepancy between the numbers of individual tropical storms and overall storm totals arises when there were no rain-rate retrievals while the tropical cyclone was at tropical storm intensity, but there was a retrieval for the same storm at hurricane intensity. Note that storms that traversed through multiple basins are given a count of one for each basin it traveled through for Table 1.

### b. Rain rates

The precipitation dataset consists of a large sample of satellite-derived rain rates from passive-microwave radiometers [i.e., the Special Sensor Microwave Imager (SSM/I), TMI, Advanced Microwave Scanning Radiometer for Earth Observing System (EOS) (AMSR-E)] from 1988 to 2002, using the latest (SSM/I version 6, TMI version 4, AMSR-E version 5) RSS retrievals (Hilburn and Wentz 2008). To unify these various sensors, the microwave radiometer brightness temperatures were intercalibrated by RSS. The differing footprint sizes from these sensors are accounted for through nonuniform beam-filling corrections in the RSS algorithm. The sea surface temperature, surface wind speed, columnar water vapor, columnar cloud water, and surface rain rate are all simultaneously retrieved by the RSS algorithm. The rain partition of the algorithm retrieves liquid water attenuation at 19 and 37 GHz to compute a total columnar liquid. This total columnar liquid is then averaged over an assumed height to produce a mean column rain rate, which is assumed to be
the surface rainfall. The brightness temperature measurements used as inputs to the algorithm have footprint sizes up to $69 \times 43$ km (for the SSM/I 19-GHz channel). However, RSS releases the retrievals on a fixed $0.25 \times 0.25$ grid. It is important to note that the RSS algorithm only retrieves rain rates over oceans beyond a 50 km buffer away from coastlines.

Cecil and Wingo (2009) examined the differences between four TRMM satellite-derived rain-rate products, including the ones used in Cecil (2007; RSS version 3) and this study (RSS version 4). The other two were the TMI 2A12 (version 6) and the Precipitation Radar (PR) 2A25 (version 6), which were scaled down to match the $0.25^\circ$ grid of the RSS rain rates to enable a direct comparison between the algorithms. Only identical pixel locations were used for the analysis. Results indicated that the majority of the differences between the products had to do with their rain-rate magnitudes, although the scaled-down 2A25 did reveal more storm structure. Overall, RSS version 3 produced a factor of 2 more rain than the other products. This was mainly because of the frequent occurrence of high rain rates, although the product limited them to $25 \text{ mm h}^{-1}$. This internal limit is not present in the updated RSS version 4 product, which instead produces the most rain around $-10 \text{ mm h}^{-1}$. The PR 2A25's higher native resolution and greater dynamic range allow for much greater rain-rate values even on the scaled-down grid. The PR 2A25 produces the second most rain within 100 km of storm center for hurricanes. Coming in last is the 2A12 with the least production of rain, mainly because of the relative lack of heavy rain. But, 2A12 does produce the most moderate rain ($-5 \text{ mm h}^{-1}$) for both tropical storms and hurricanes. These findings are important because it shows how using different products may result in differences of precipitation magnitude, but the overall spatial trends associated with the precipitation field remain close.

The RSS rain rates were averaged over a polar grid consisting of 50-km radial bins out to 400 km, sliced by $45^\circ$ azimuthally. The grid is aligned along the vertical wind shear vector in this paper. The rain composites have the polar grid contoured for simplicity. Using the same polar grid as for the mean rain rates, composites of rain coverage were constructed. This consists of the ratio of raining $0.25^\circ \times 0.25^\circ$ pixels versus the total number of pixels in each bin. Composites of heavy rain coverage were created similarly, using rain-rate values $>8 \text{ mm h}^{-1}$. This value was obtained by examining histograms (Fig. 1; adapted from Cecil and Wingo 2009) of rain rates. Over a quarter degree grid, $8 \text{ mm h}^{-1}$ is a relatively "heavy" rain rate. Figure 1 indicates that rain rates at $8 \text{ mm h}^{-1}$ and above give a sizeable contribution to tropical cyclone rainfall in the RSS algorithm. To examine the high end of the rain-rate distribution, we also compute the 95th percentile of the $0.25^\circ$ rain rates.

c. Vertical wind shear

Environmental vertical wind shear (200–850 hPa) was computed for each satellite overpass using ERA-40 (Uppala et al. 2005) model data at 1.125$^\circ$ resolution between 1 January 1988 and 31 August 2002. Often times the ERA-40’s location for storm center did not completely agree with the best-track fix. Since the model’s representation of the storm center is more important than the best track’s for the shear calculation, an attempt to find the ERA-40 storm center was implemented. The location of the ERA-40 925-hPa grid box with the highest absolute vorticity within a 150-km radius from the best-track fix takes precedence over the best-track fix as the storm location. Prior to the shear vector calculation, the TC vortex was removed following a method suggested by M. DeMaria (2007, personal communication), where the mean radial and tangential winds are subtracted out as a function of range.
Next, the mean wind vector was computed over a 200–800-km annulus. An annulus is used to reduce contamination in the shear calculation for two main reasons: 1) attempts to correct for the disagreement between the ERA-40 and best-track fix may have been unsuccessful and 2) some remnants of the vortex may be present even after the winds are filtered. To complete the shear calculation, the 850-hPa mean wind vector is subtracted from its 200-hPa counterpart. The shear vector values are then linearly interpolated between the 6-h ERA-40 time periods to match the time of the satellite overpass.

Following earlier studies, shear has been broken down into three categories: weak ($<5$ m s$^{-1}$), moderate (between 5 and 10 m s$^{-1}$), and strong ($>10$ m s$^{-1}$). Figure 2b shows that the strong shear sample is the smallest with 1605 cases, while the moderate sample is the largest with 2505. The peak number of cases occurs for hurricanes with 5 m s$^{-1}$ of shear, which is the minimum threshold for the moderate category. This is perhaps a poor place to split the “weak” and “moderate” samples; although further investigation revealed little change within the results when applying different bounds for the shear categories (not shown in this paper). For the hurricane sample set, the maximum and minimum shear magnitudes are 36 and 0.1 m s$^{-1}$, respectively. The majority of hurricanes experience southwesterly or westerly shear, with a secondary peak of northeasterly shear (Fig. 2a). Northeasterly shear is most common within the northeastern Pacific Ocean basin.

As in most prior studies, we focus on deep-layer (200–850 hPa) vertical shear. It is worthwhile to question whether this is the most appropriate layer, since updrafts and available moisture are rooted at low levels. A preliminary examination using shallower layers yields similar results—rain is favored in the downshear-left quadrant whether the shear vector is defined over the 200–850-, 500–850-, or 700–925-hPa layer (Figs. 3a–c). The shear vectors over these layers usually have similar directions. For the small subset of cases where shear vectors for these layers are out of phase with each other, the rain tends to be maximized downshear left relative to the deep-layer shear (not shown). Further analysis is needed to investigate these relationships more thoroughly. This is left for future work.

![Fig. 2](image-url) (a) 200–850-hPa shear direction and (b) magnitude for the entire hurricane sample set from all tropical cyclone basins.

![Fig. 3](image-url) Composite mean hurricane rain rates relative to the (a) 200–850-, (b) 500–850-, and (c) 700–925-hPa shear vector.
3. Results

a. Hurricanes under varying shear

As the previous numerical, observational, and passive-microwave studies have shown, hurricane precipitation is favored downshear-left with the amplitude of this displacement increasing with stronger shear (Figs. 4a–c). For hurricanes in weakly sheared environments (<5 m s\(^{-1}\); Fig. 4a) mean rain rates are fairly symmetric. The weak asymmetry is most easily seen within 100 km from storm center in Fig. 4a. However, a “left-of-shear” and downshear bias is present, contrary to the symmetric pattern one might expect from the mean. This asymmetry can be explained by a few possibilities. First, errors associated with the shear calculation and/or model data may have underestimated the shear vector’s magnitude. Second, stronger shear may have been present prior to the satellite’s overpass, with the rain field still exhibiting the effects (this topic will be discussed later in this paper). A histogram of shear magnitude (Fig. 2b) indicates the majority of “weak shear” cases lie within the upper bounds of their category’s magnitude (\(\sim 4\) m s\(^{-1}\)). Other possibilities are that even weak shear truly is enough to induce this asymmetry, or some other factor (e.g., storm motion) systematically favors this asymmetry.

Moderately sheared (5–10 m s\(^{-1}\)) hurricanes (Fig. 4b) display a stronger downshear asymmetry than weakly sheared storms, with the left-of-shear bias increasing as well. Again, Fig. 2a shows the peak occurrence of the shear magnitude occurring at 5 m s\(^{-1}\) and then decreasing as the shear magnitude increases. This implies that the moderate cases are a modification of the weaker cases with the addition of samples with only slightly greater shear.

As previous observational studies utilizing passive-microwave-derived rain rates have shown (Chen et al. 2006; Cecil 2007), hurricane rain patterns in a strongly sheared environment (\(>10\) m s\(^{-1}\); Fig. 4c) are very asymmetric, with a pronounced downshear-left preference. Cecil (2007) showed that differences around the inner core were greatest for strongly sheared Atlantic hurricanes with the mean rain rates ranging between 15.6 and 6.1 mm h\(^{-1}\). Chen et al. (2006) also demonstrated that the relative asymmetry of the precipitation field was maximized under strong (>7.5 m s\(^{-1}\)) shear. The main reason for the discrepancy between the rain-rate magnitudes used in this study versus Cecil (2007) arises from the overestimation of rain rates by the algorithm used by Cecil (2007; RSS version 3). Figure 4c illustrates for this study, within the inner core between 50- and 100-km radii, mean rain rates range from 10.2 (downshear left) to 2.7 mm h\(^{-1}\) (upshear right). That is nearly a factor of 4 difference from the favored region (270°–315° with respect to the shear vector) to the suppressed region (90°–135°). The moderate shear sample has over a factor of 2 difference (9.5 versus 4.5 mm h\(^{-1}\)) between these regions. The difference across the inner core is much smaller for the weakly sheared sample (8.5 versus 6.0 mm h\(^{-1}\)).

Next we examine whether these differences in mean rain rates result from differences in how often it rains (or over how large an area), or from differences in the magnitude of the smaller scale rain rates. When considering rain coverage and heavy rain coverage, note that those are based on a 0.25° × 0.25° grid spacing with contributions from larger radiometer fields of view. If part of that grid box is raining (enough to be detected by the RSS microwave algorithm), the entire grid box will be assigned a nonzero rain rate. A good example of this is found in Figs. 5 and 6. Although the eye of Paka (1997) has a near rain-free region, the RSS rain-rate product overestimates the rain by assigning values of around 8 m h\(^{-1}\). The higher-resolution PR shows it as being rain free. In contrast, in regions where light precipitation occurs in an area much smaller than the footprint size of

Fig. 4. Mean rain rates for hurricanes with shear (a) <5, (b) 5–10, and (c) >10 m s\(^{-1}\). Contours of 4 and 8 mm h\(^{-1}\) are in bold.
the passive-microwave sensors, little or no rainfall is registered in the RSS retrieval.

The rain coverage plots (Figs. 7a–c) are much more symmetric than their mean rain-rate counterparts. Even across the inner core, values differ only by 20% (97%–77%) under strong shear and only 2% (98%–96%) for weak shear. This 20% decrease from the downshear left to upshear right is indicative that a downshear-left bias is present; however, it is far smaller than the factor of 4 difference seen in the same bins for mean rain rates. The rain coverage asymmetry is similar in shape, but, much smaller in amplitude than the mean rain asymmetry. Therefore, this factor of 4 difference for mean rain is not a result of it raining 4 times as often in one region than the other. Most of the inner core is raining at the scale of the retrievals, whether it is highly sheared or not. The difference must come from the occurrence of heavy rain instead.

Heavy rain (>8 mm h\(^{-1}\)) coverage plots (Figs. 8a–c) hold very similar shapes compared to their mean rain-rate counterparts. The downshear-left bias is present for weakly sheared storms and increases in magnitude with stronger shear. Also, the largest differences occur in the inner core at the same bins as for the mean rain rates. The differences for heavy rain coverage are even greater than those found in the previous comparisons for mean rain rates. Heavy rain coverage for strongly sheared storms varies from 72% (downshear left) to 9% (upshear right), a factor of 8 difference and twice the amount of difference seen for the inner-core mean rain rates. These relative differences in the heavy rain coverage remain larger than their mean rain-rate counterparts, although they become smaller as shear weakens. Large, heavy precipitation particles fall with a greater terminal fall speed, and thus are not advected as far around the cyclone. Low-density particles associated with lighter rain can be spread more easily around the vortex before falling to the surface.

In the preferred regions, “heavy rain” extends well beyond values of 8 mm h\(^{-1}\). The 95th percentile level is around 13 mm h\(^{-1}\) in the inner core for all quadrants in the weak shear composite (Fig. 9a). The 95th percentile is only 11 mm h\(^{-1}\) in the inner part of the upshear-right region for the strongly sheared composite (Fig. 9c), and quickly decreases outward to 4 mm h\(^{-1}\) at the 200-km radius. In the favored downshear-left region, the 95th percentile is over 15 mm h\(^{-1}\) in the inner core and values over 11 mm h\(^{-1}\) extend outward through the 350-km

**Fig. 5.** RSS rain rates for a TRMM overpass of Super Typhoon Paka (1997). Contours are 0.01, 4, 8, 12, and 16 mm h\(^{-1}\). Overlaid is the 850–200-hPa shear vector.
radius. It must be emphasized that the precise rain-rate values (not necessarily the patterns) are strongly dependent on the particular rain-rate retrieval. From Cecil and Wingo (2009), the TRMM PR 2A25 algorithm (even scaled down to 0.25° resolution) would give much higher 95th percentile values.

The absolute differences in mean rain rates are greatest in the inner core, but the relative differences are greater when including the outer regions. Table 2 lists the total 0–400-km area-weighted mean rain rates for each quadrant, with respect to the shear vector. The difference between the preferred and suppressed quadrants is notably greater even for weakly sheared storms (2.4 versus 1.5 mm h⁻¹), but for strongly sheared storms the difference is more than a factor of 7 (4.6 versus 0.6 mm h⁻¹). Moderately sheared cases experience

![Fig. 6. PR 2A25 version 6 rain rates for the same TRMM overpass of Super Typhoon Paka (1997) displayed in Fig. 5. Contours are 0.1, 8, and 32 mm h⁻¹. Overlaid is the 850–200-hPa shear vector.](image)

![Fig. 7. Rain coverage for hurricanes with shear (a) <5, (b) 5–10, and (c) >10 m s⁻¹. Contour of 50% coverage is in bold.](image)
a factor of three difference (3.2 versus 1.1 mm h\(^{-1}\)), a modest gain compared to their inner-core difference.

Significant differences also occur across regions other than the “preferred” or downshear-left quadrants and the “suppressed” or upshear-right quadrants. The downshear-right 0–400-km area-weighted mean rain rates are only slightly greater than their upshear-left counterparts, when shear is >5 m s\(^{-1}\) (Table 2). They are equivalent under weak shear. Comparing the 0–400-km area-weighted mean rain rates for the downshear and upshear semicircles, we find that the downshear half values are basically a factor of 2 greater than those found in the upshear half for moderate shear and a factor of 3 greater for strong shear. When comparing the left and right of shear semicircles, the difference between the two increases in favor of the left as shear increases. The difference is small for weak shear (2.2 versus 1.7 mm h\(^{-1}\)), but increases to over a factor of 2 for strong shear (3.1 versus 1.2 mm h\(^{-1}\)).

Although mean rain-rate values are compared for the inner core and quadrants of the samples, it is important to note that the rain rates are not “conserved” as a function of radius while varying the shear. That is, the rain is not simply “shifted” from right to left and from upshear to downshear at the same radius as Fig. 10 shows. Instead, an overall reduction occurs within the inner core as a function of increasing shear. This reduction is accompanied by relatively higher mean rain rates beyond approximately the 150-km radius, which is indicative of the precipitation being displaced farther away from the storm center with stronger shear.

b. Strong shear, varying TC intensity

Above, the effect of environmental shear on hurricanes was examined by breaking down the magnitude of shear into three categories. Next, the relationships for the precipitation field in a strongly sheared environment are examined by dividing tropical cyclone intensity into three categories. By doing so, it allows us to compare how storms of varying intensity respond in a strong shear environment.

Mean rain rates for tropical storms under a strong shear environment are biased toward the downshear-left quadrant as seen in Fig. 11a. The peak mean rain-rate

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Fig. 8. Heavy rain coverage for hurricanes with shear (a) <5, (b) 5–10, and (c) >10 m s\(^{-1}\). Contour of 50% coverage is in bold.

Fig. 9. The 95th percentile rain rates for hurricanes with shear (a) <5, (b) 5–10, and (c) >10 m s\(^{-1}\). Contours of 4, 8, and 12 mm h\(^{-1}\) are in bold.
value (5.1 mm h\(^{-1}\)) is half that found in the hurricane sample (10.2 mm h\(^{-1}\)) in Fig. 4c. The location of the rain-rate maximum for tropical storms is farther downshear (100–150 versus 50–100 km for hurricanes), with less of a left-of-shear bias (315°–360°) than for hurricanes (270°–315°). The area-weighted mean rain rate for the downshear-left quadrant is 2.9 mm h\(^{-1}\) (Table 3), and over 80% of the rain is in the downshear semicircle. The cyclonic advection of precipitation about the storm center is less intense for tropical storms because of a relatively weaker tangential wind field.

Figures 11b,c break down the hurricane sample (Fig. 4c) into category 1–2 (CAT12; maximum sustained winds between 32 and 48 m s\(^{-1}\)) hurricanes versus category 3–5 (CAT35; maximum sustained winds >48 m s\(^{-1}\)) hurricanes. For both, the mean rain-rate maxima are found in the bin located with a 50–100-km radius, and 270°–315° relative to the shear vector. Peak values of mean rain rate increase from 9.5 mm h\(^{-1}\) for CAT12 to 12.4 mm h\(^{-1}\) for CAT35 hurricanes. Directly across the inner core in the suppressed upshear-right region, the mean values are 2.0 and 4.7 mm h\(^{-1}\), respectively. The results are a 475% and 264% ratio across the inner core (1275% for tropical storms; 5.1 versus 0.4 mm h\(^{-1}\)), indicating a decline in the asymmetry with increasing hurricane intensity. This seems to contradict Ueno’s (2007) conclusion that the amplitudes of vertical motion and precipitation asymmetries increase with increasing shear magnitude and increasing vortex strength. More generally, major hurricanes do tend to appear more symmetric (e.g., Dvorak 1975; Willoughby et al. 1984). A preference for the downshear left still exists in the strongest hurricanes, but significant precipitation occurs around the entire storm. For weaker CAT12 storms, the structure may not be as well organized, thus the majority of the convection (and precipitation) would be displaced downshear left. To some extent, this difference can be explained by stronger tangential winds distributing the precipitation particles into a more symmetric pattern. Ueno’s model did not account for horizontal advection of precipitation. The weaker asymmetry in stronger storms may also be attributed to a more vertically coherent and stiff vortex resisting the tilting influence of the shear. Reasor et al. (2004) argued that a vortex Rossby wave damping mechanism limits the tilt in stronger storms. But on the other hand, strong shear and asymmetric organization tend to prevent a TC from attaining (or maintaining) major hurricane intensity (e.g., Tuleya and Kurihara 1981; DeMaria 1996). It is important to note that passive-microwave rain retrievals are averaged over a layer, and are most responsive to midlevels. Hydro-meteors can travel tens of kilometers horizontally while only falling a few kilometers in tropical cyclones. The

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<td>400</td>
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**Fig. 10.** Hurricane mean rain rates as a function of radius and shear magnitude.
actual surface rain may differ, depending upon the precipitation’s intensity, depth, areal coverage, and composition (e.g., liquid, ice, and mixed-phase particles aloft).

Rain coverage also becomes much less asymmetric as TC intensity increases (Figs. 12a–c). For strongly sheared tropical storms, the strong asymmetry associated with the mean rain rates carries over into the rain coverage. Unlike the hurricane sample (Fig. 7a), most of the suppressed upshear-right region in tropical storms is simply not raining (at least as represented by this passive-microwave retrieval). Quantitatively, the values across the tropical storm “core” (100–50 km and 315°–360°) range from 84% (downshear left) to 28% (upshear right) for rain coverage, and from 30% to 2% for heavy rain coverage (Fig. 13a). In comparison, the rain coverage asymmetry for CAT12 hurricanes is drastically reduced with inner-core values ranging from 97% to 69%. Similar patterns occur in heavy rain coverage. As TC intensity increases, so do the overall percentages for heavy rain coverage; however, the relative asymmetry decreases. Even in the upshear-right quadrant, 95% of the grid boxes have rain in the inner core of CAT35 hurricanes. The differences for heavy rain coverage around the core of the samples are a factor of 15 (30% versus 2%) for tropical storms, a factor of 9 (66% versus 6%) for CAT12 hurricanes, and over a factor of 4 (92% versus 20%) for CAT35 hurricanes. Again, the trend and magnitude of these values are in line with the differences found in the mean rain rates for the same bins, suggesting that heavy rain is responsible for a great deal of the asymmetry within the precipitation field.

The 95th percentile rain rates have a dramatic asymmetry for strongly sheared tropical storms (Fig. 14a). The downshear-left values are over 13 mm h⁻¹, only slightly less than the values for hurricanes. These high rain-rate values extend out for a few hundred kilometers. But our innermost grid points in the upshear-right region have only 7 mm h⁻¹ at the 95th percentile level, and this quickly drops below 3 mm h⁻¹ beyond the 100-km radius. The upshear-right region of major hurricanes (Fig. 14c) is not as suppressed, with 12 mm h⁻¹ for the 95th percentile near the center and 5 mm h⁻¹ at the 200-km radius.

Examining the 0–400-km area-weighted mean rain rates between the quadrants (Table 3) illustrates how the asymmetry varies with intensity between the downshear-left and upshear-right quadrants. The ratios between these regions for tropical storms and CAT12 hurricanes are similar to one another with values of 967% (2.9 versus 0.3 mm h⁻¹) for tropical storms, a factor of 9 (4.5 versus 0.5 mm h⁻¹) for CAT12 hurricanes. Major hurricanes see this ratio drop to 533% (4.8 versus 0.9 mm h⁻¹).

c. Strong shear in different TC basins

The plots in Fig. 15 are similar to Fig. 4c (mean rain rates for hurricanes encountering strong shear), but they are divided among TC basins. Each individual basin has results that are consistent with the previous composites. Precipitation is displaced downshear and left (right for the SH; Fig. 15f) of the shear vector. The northwestern Pacific (NWP; Fig. 15e) has the broadest mean precipitation field and the greatest total 0–400-km area-weighted mean rain rate (2.5 mm h⁻¹; Table 4). It also has the most robust sample size. The northeast Pacific (NEP) is the most compact (Fig. 15d) and the most asymmetric across the inner core with mean rain rates

<table>
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<th>Table 3. As in Table 2, but for tropical cyclones in strongly sheared (&gt;10 m s⁻¹) environments.</th>
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<td>Tropical storms</td>
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ranging from 10.8 to 2.0 mm h\(^{-1}\), over a factor of 5 difference. The comparable numbers for all basins in Fig. 4c were 10.2 versus 2.7 mm h\(^{-1}\). However, note that the NEP sample size is limited to 53 because of a relative lack of strong shear in the heart its basin. Chen et al. (2006) noted that the NEP had the most symmetric rain distributions, but their composites for each basin included the weaker shears that are especially common in the NEP. The SH has the greatest orthogonal displacement of precipitation relative to the shear vector. The ratio between the left and right of shear semicircle area-weighted mean rain rate for the SH is 290% (1.0 versus 2.9 mm h\(^{-1}\)), which is 40% greater than that found for the NWP. The small sample size for the central Pacific (11 overpasses; Fig. 15b) does not produce results robust enough for individual analysis.

d. Varying shear direction

Another question raised is whether the direction of the environmental shear has any bearing on the precipitation field. Tuleya and Kurihara (1981) numerically showed that for the Atlantic basin, easterly shear favored tropical cyclone development and westerly shear inhibited it. Ritchie and Frank (2007) demonstrated that this may be due in part to the advection of planetary vorticity by the tropical cyclone with findings demonstrating that such forcing would generate northwesterly beta-gyre shear. This would suggest that environmental shear from the east (especially southeasterly) would be naturally weakened and the opposite would occur for westerly (especially northwesterly) environmental shear.

As Figs. 16a–d indicate, a strong preference for the downshear-left quadrant exists regardless of shear direction when shear is >10 m s\(^{-1}\). The southeasterly shear sample in Fig. 16d is the least asymmetric within the inner core (100 km) with values ranging from 9.5 to 3.8 mm h\(^{-1}\), which may perhaps be due to its small sample size (63 overpasses). The magnitude of the inner-core asymmetry for northwesterly shear (9.8 versus 1.8 mm h\(^{-1}\); Fig. 16a) is more than double its southeasterly counterpart and has substantially larger sample

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**FIG. 12.** Rain coverage for (a) tropical storms, (b) CAT12 hurricanes, and (c) CAT35 hurricanes in a strong shear environment (>10 m s\(^{-1}\)). Contour of 50% is in bold.

**FIG. 13.** Heavy rain coverage for (a) tropical storms, (b) CAT12 hurricanes, and (c) CAT35 and above hurricanes in a strong shear environment (>10 m s\(^{-1}\)). Contour of 50% is in bold.
Precipitation with northeasterly shear (Fig. 16b) is slightly more symmetric (11.4 versus 3.9 mm h\(^{-1}\)) than with southwesterly shear (10.2 versus 2.8 mm h\(^{-1}\); Fig. 16c) within the inner core. The differences between the plots in Figs. 16a–d are not attributable to TC intensity, as both the median (\(-43\) m s\(^{-1}\)) and mean (\(-41\) m s\(^{-1}\)) TC intensities vary little between the four samples. The differences are consistent with an enhancement by the beta gyre, as in numerical studies by Tuleya and Kurihara (1981), Ritchie and Frank (2007), and others.

e. Storm motion versus shear

Another important factor to consider when discussing environmental influences on hurricane rainfall asymmetry is storm motion. In this section, the manner by which mean rain rates in hurricanes are distributed as a function of both storm motion and vertical wind shear is examined. To do this, a similar methodology employed by Corbosiero and Molinari (2002) is followed. The plots in Figs. 17a–d are oriented such that the shear vector is oriented upward, but storm motion is separated into four
groups according to their relative angle from the shear vector. For these plots, there is a minimum threshold of 5 m s$^{-1}$ for both storm motion and shear magnitude.

Regardless of the direction of storm motion, the downshear-left quadrant is favored in all the plots. For hurricanes that have their shear vector within 45$^\circ$ of storm motion (“along motion,” Fig. 17a), an asymmetric distribution of rainfall to the front left of storm motion is visible, which is the downshear-left region here as well. When the shear vector is to the right of storm motion (Fig. 17b), the front-right (motion) and downshear-left quadrants coincide, creating by a small margin the most asymmetric pattern (9.9 versus 2.9 mm h$^{-1}$). When the shear vector is against storm motion (Fig. 17d), the preferred region is to the right rear of storm motion and downshear left of the shear vector. Figure 17c exhibits the least asymmetric pattern (10.0 versus 4.5 mm h$^{-1}$) between the four, when shear is oriented to the left of storm motion. This relative symmetry in Fig. 17c is not due to a lack of strong shear cases, but rather a relatively large number of strong hurricanes (192 CAT35 hurricanes). These findings are consistent with previous studies (Corbosiero and Molinari 2003; Chen et al. 2006; Ueno 2007).

f. Shear’s lag effect

As previously mentioned in section 3a, the precipitation field may exhibit residual effects from vertical shear that occurred prior to the satellite’s overpass, or a “lag effect.” Here, a straightforward analysis of the precipitation field is performed by comparing samples according to the magnitude of the shear vector at times leading up to the overpass. For these comparisons, different shear categories than those used in the previous sections are applied to increase the sample size. Here, 5 m s$^{-1}$ is still used for “weak shear,” but now 7.5 m s$^{-1}$ is the threshold for the “strong” shear sample.

One of the previously hypothesized possibilities for the downshear left bias found in weaker shear cases (Fig. 4a) was that stronger shear occurred prior to the overpass. Figure 18a shows that this is likely not the explanation. It retains the downshear-left bias found in Fig. 4a, despite the fact that Fig. 18a is composed of overpasses that had shear $<$5 m s$^{-1}$ throughout the 12 h prior to the satellite’s overpass. It is important again to note that the accuracy of the shear magnitude is limited to both the model data and the method used for the shear calculation.

Hurricanes in a weakly sheared environment at the time of the overpass, but moderate-to-strong shear (>7.5 m s$^{-1}$, Fig. 18c) 12 h prior, somewhat resemble other storms with weak shear (Figs. 4a and 18a). However, Fig. 18c is noticeably more asymmetric than Figs. 4a and 18a, especially when comparing the downshear-left and upshear-right quadrants within a 100-km radius. There, the ratio is 136% (8.3 versus 6.1 mm h$^{-1}$) for Fig. 18a and 171% (8.9 versus 5.2 mm h$^{-1}$) for Fig. 18c. Recall that this ratio for the weak shear sample (Fig. 4a) is 142% (8.5 versus 6.0 mm h$^{-1}$). This evidence illustrates that while some effects from the stronger shear still remain in Fig. 18c, the precipitation field is able to regain characteristics closely resembling the weaker shear samples over only 12 h.

Storms that have shear >7.5 m s$^{-1}$ at the time of the overpass, but $<$5 m s$^{-1}$ 12 h prior (Fig. 18d), retain similar characteristics (a factor of 2 difference across the inner core; 8.8 versus 4.3 mm h$^{-1}$) held by the moderate and strong shear composites for hurricanes (Figs. 4b, c). But, the sample in Fig. 18d is more symmetric than the sample for hurricanes, which encountered shear >7.5 m s$^{-1}$ throughout the 12 h prior to the overpass (Fig. 18b; a factor of 3.7 difference across the inner core; 10.1 versus 2.7 mm h$^{-1}$). However, Fig. 18d is more asymmetric than both Figs. 4a and 18a. Such evidence suggests that the hurricane precipitation field responds rather quickly to changes in the shear. Perhaps a shorter temporal “lag” exists, but an investigation of a 6-h “time lag” would not have provided a robust enough sample with the current dataset.

Rogers et al. (2003) found similar results with their simulation of Hurricane Bonnie (1998). During the early stages of the model run, Bonnie (1998) attained a very asymmetric profile under shear between 20 and 25 m s$^{-1}$ (900–400 hPa). Within a 6 h period, the shear weakened to 5–10 m s$^{-1}$ (900–400 hPa) during which time the storm became increasingly symmetric nearly simultaneously as shear decreased. It is important to note that this was an individual case and that they calculated shear over a thinner layer than was used in this study.

4. Summary and conclusions

The response of the precipitation field of TCs in relation to vertical wind shear has been examined using a robust
sample set of satellite-derived rain rates from 1 January 1988 to 30 August 2002. The sample consisted of 20,028 TC snapshots from 620 individual hurricanes and 1108 individual tropical storms. Rain rates were rotated according to the 200–850-hPa shear vector, and then averaged over a regular polar grid. Rain coverage, heavy rain coverage, and 95th percentile rain rates were also presented in the same manner using the same grid as for the mean rain rates.

The effect that vertical wind shear has on the precipitation field of tropical cyclones is mainly dependent upon two variables: 1) the magnitude of the shear vector and 2) tropical cyclone intensity. The data shown here illustrates the precipitation is favored downshear left (right for SH) even for the “weaker” shear category (<5 m s⁻¹). The amplitude of this asymmetry becomes larger for stronger shear. For the weak shear sample, the difference across the inner core (270°–315° versus 90°–135° with respect to the shear vector and at a radius of 50–100 km) is about a factor of 1.4. This difference increases to nearly a factor of 4 for the strong shear sample. If the magnitude of shear is kept constant, but tropical cyclone intensity varies, we see that the asymmetry is reduced as tropical cyclone intensity increases. That is, weaker systems such as tropical storms are generally more responsive to vertical wind shear than are category 2 hurricanes. These findings hold true regardless of ocean basin. This appears to contradict the formulation by Ueno (2007, 2008) that stronger shear

![Image](image_url)
and a stronger vortex both favor a greater amplitude asymmetry. This difference may be partly because Ueno's model does not include horizontal advection of precipitation by the tropical cyclone's winds.

Similar mean rain-rate patterns were found with respect to shear computed over shallower layers. The downshear-left quadrant is favored, whether the shear vector was defined over the 200–850-, 500–850-, or 700–925-hPa layer. The shear directions for these layers are usually similar to each other. When they are substantially out of phase with each other, the rain tends to be more focused in the downshear-left region relative to the deep-layer (200–850 hPa) shear vector. This conclusion is based on an admittedly small subset of the data, and further examination may be warranted.

Heavy rain coverage is much more asymmetric than rain coverage. The asymmetries of both follow the trends seen in the mean rain-rate plots. However, heavy rain coverage retains a greater amplitude asymmetry than its mean rain-rate counterparts. This indicates that the majority of the asymmetry seen in the mean rain-rate field is primarily due to the asymmetry occurring from heavy rain.

Strong shear with a westerly component produces a more “focused” downshear-left mean rain-rate pattern than the easterly counterparts. The two easterly samples tend to have more precipitation occur in the upshear-left quadrant, although precipitation is still primarily favored downshear left. Strong southeasterly shear has the least asymmetric precipitation field.
between the four, but suffers from a small sample size. While these results are not very robust, they are in line with what would be expected according to theory and the numerical modeling studies (e.g., Tuleya and Kurihara 1981; Ritchie and Frank 2007).

When hurricanes are moving faster than 5 m s\(^{-1}\) and are experiencing shear greater than 7.5 m s\(^{-1}\), regardless of the orientation between storm motion and the shear vector, precipitation is displaced downshear and to the left of the shear vector. The amplitude of this displacement is weakest for cases in which the shear vector is to the left of storm motion; however, this is primarily due to a relatively large number of strong hurricanes. When the shear vector is oriented along storm motion, the sample is dominated by weaker hurricanes which in turn produce the lowest mean rain rates compared to the other three samples.

Results presented in this study indicate that shear’s impact on hurricane rainfall is somewhat immediate. Hurricanes that endure moderate-to-strong shear 12 h prior, but weak shear at the time of the satellite overpass were more symmetric than storms that encounter moderate-to-strong shear at the time of the overpass and more asymmetric than storms that encountered weak shear throughout the 12 h prior to the overpass. Similarly, hurricanes in a moderate-to-strong shear environment at the time of the overpass, but weak shear 12 h prior were more symmetric than the sample that
endured moderate-to-strong shear throughout the 12 h prior to the overpass and were more asymmetric than the weak shear samples. Higher temporal resolution model data would be needed to further investigate to what extent the “lag effect” on the precipitation field occurs.

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**REFERENCES**


