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The Effects of Gap-Wind-Induced Vorticity, the Monsoon Trough, and the ITCZ on Tropical Cyclogenesis

Heather Holbach

THE FLORIDA STATE UNIVERSITY
COLLEGE OF ARTS AND SCIENCES

THE EFFECTS OF GAP-WIND-INDUCED VORTICITY, THE MONSOON TROUGH, AND
THE ITCZ ON TROPICAL CYCLOGENESIS

By

HEATHER HOLBACH

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The members of the supervisory committee were:

Mark Bourassa
Professor Directing Thesis

Robert Hart
Committee Member

Guosheng Liu
Committee Member

Mark Powell
Committee Member

The Graduate School has verified and approved the above-named committee members, and certifies that the thesis has been approved in accordance with university requirements.

This thesis is dedicated to my family for all of their love, support, and encouragement.

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ABSTRACT

Tropical cyclogenesis in the eastern North Pacific (EPAC) basin is related to gap-wind-induced vorticity, the monsoon trough, and the intertropical convergence zone (ITCZ). There are several gaps in the Central American Mountains, on the eastern edge of the EPAC basin, through which wind can be funneled to generate surface wind jets (gap winds). This study focuses on gap winds that occur over the Gulf of Papagayo and the Gulf of Tehuantepec. QuikSCAT (QSCAT) 10 m equivalent neutral winds are used to identify gap wind events that occur during May through November of 2002–2008. Dvorak fix locations, GridSAT IR data, and National Hurricane Center Tropical Cyclone (TC) Reports are used to track the disturbances that occurred during the study period. Surface vorticity is tracked using the QSCAT winds and the contribution of vorticity from the gap winds to the development of each disturbance is categorized as small, medium, or large. Cross-calibrated multiplatform (CCMP) surface wind data are used to verify the tracking of QSCAT computed vorticity and to identify when the monsoon trough and the ITCZ are present. It is found that gap winds are present over the Gulf of Papagayo and the Gulf of Tehuantepec for more than 50% of the QSCAT coverage days and that these gap winds appear to contribute to the development of disturbances in the EPAC. Considerably more TCs form when the monsoon trough is present versus the ITCZ and the majority of the contributions from the gap winds also occur when the monsoon trough is present.

CHAPTER ONE

INTRODUCTION

The circumstances under which a tropical cyclone (TC) forms are still a highly debated and not well-understood topic within the field of meteorology. Many theories exist for tropical cyclone formation, such as conditional instability of the second kind (CISK; Charney and Eliassen 1964; Ooyama 1964) and wind-induced surface heat exchange (WISHE; Emanuel 1986; Emanuel et al. 1994). In CISK and WISHE, which are both “bottom-up” theories, the feedback loop begins at the surface. Other bottom-up theories involve low-level cyclonic vorticity maxima, induced by convection, that merge over time to create a larger low-level cyclonic vorticity maximum (Montgomery and Enagonio 1998; Enagonio and Montgomery 2001). “Top-down” theories (Ritchie and Holland 1997; Simpson et al. 1997) also exist. According to these theories, mesoscale convective vortices produce a mid-level cyclonic vorticity maximum that enhances the low-level cyclonic vorticity. Although none of these theories can completely explain tropical cyclogenesis, they all propose that there must be an initial region of low-level, or surface, cyclonic vorticity present. An increased understanding of tropical cyclogenesis would allow forecasters to more accurately predict which disturbances will develop into TCs and improve the general knowledge about TCs.

This study focuses on tropical cyclogenesis in the eastern North Pacific (EPAC) basin. This basin is unique in that it has the highest density of TC formation of all of the tropical cyclone basins (Renard and Bowman 1976). It has been suggested that most of the TCs that form in the EPAC originate from tropical disturbances formed in the Atlantic basin or from easterly waves that traverse the Atlantic Ocean (Avila 1991; Avila and Pasch 1992; Shapiro 1986). In this model, some of the disturbances or easterly waves that do not generate TCs in the Atlantic propagate into the Pacific. However, there is another unique feature to this basin, which is the presence of the Central American Mountains on the western edge of the basin. This mountain range has peak elevations of 2000–3000 m and several mountain gaps (Fig. 1) where the elevation reaches only about 250 m (Steenburgh et al. 1998). This study aims to determine how surface vorticity generated by winds funneled through the gaps in the Central American

Mountains, creating a surface wind jet (gap winds) over the Gulf of Papagayo and the Gulf of Tehuantepec (Fig. 2), influences the development of TCs in the EPAC.

Fig. 1. Topographical map depicting the mountain gaps in the Central American Mountains (Chelton et al. 2000). Red circles indicate the mountain gaps of interest to this study.

Fig. 2. Example of a gap wind jet over the Gulf of Tehuantepec.

Many of the previous studies related to this topic have investigated how the Central American Mountains interact with African easterly waves, the intertropical convergence zone

(ITCZ), and the monsoon trough. Studies using computer models found that flow incident on the terrain similar to the Central American mountains is deflected around the mountains and through the gaps, generating cyclonic surface vorticity in the lee of the mountains (Mozer and Zehnder 1996; Zehnder 1991; Zehnder and Gall 1991). Other studies have used a combination of computer models and reanalysis data to look at specific TCs to determine how the mountains influenced their development (Farfàn and Zehnder 1997; Zehnder and Powell 1999). These studies found that cyclonic surface vorticity occurring in the presence of an easterly wave, the ITCZ, or the monsoon trough could lead to the development of a TC. Reanalysis data also used to complete another case study showed enhanced low-level flow through the Isthmus of Tehuantepec that occurred ahead of a 700mb African easterly wave (Molinari et al. 2000). However, without any observational data available for verification, Molinari et al. could only hypothesize that when the 700mb wave moved westward into the EPAC, it coupled with the surface cyclonic vorticity generated by the wind jet through the Isthmus of Tehuantepec to initiate cyclogenesis.

These previous studies focused on the gap winds generated through the Isthmus of Tehuantepec and did not consider how gap winds generated over the Gulf of Papagayo might contribute to tropical cyclogenesis in the EPAC. The data to confirm the theories from the previous studies was also limited, mainly to ship and buoy observations, prior to the launch of QuikSCAT (QSCAT) in 1999. The QSCAT remotely sensed wind data tremendously increased the spatial and temporal coverage of surface winds over the oceans. There are two objectives for this study: (1) to use QSCAT wind data to determine how gap-wind-induced vorticity over the Gulf of Papagayo and Gulf of Tehuantepec contribute to tropical cyclogenesis in the EPAC and (2) to determine how the ITCZ and the monsoon trough interact with the gap winds to influence tropical cyclogenesis in the EPAC.

Two case studies, 2004 Hurricane Celia and 2006 Hurricane John, are used to illustrate and discuss the methods and the results of the study. Chapter 2 discusses the data and the process for identifying gap winds and summarizes the gap wind events that occurred from May through November of 2002 through 2008. Next, the process for tracking the disturbances is presented in chapter 3, followed by a description of the method for calculating and tracking the propagation of surface vorticity along with the developing disturbances (chapter 4). In chapter 5, the propagation of vorticity seen in QSCAT is verified using cross-calibrated multiplatform

(CCMP) wind data. A description of gap wind contribution categories and a summary of the contributions follow in chapter 6. Chapter 7 contains a comparison between the occurrence of gap wind contributions, the monsoon trough, and the ITCZ. The conclusions are given in chapter 8.

CHAPTER TWO

IDENTIFYING GAP WIND EVENTS

The Jet Propulsion Laboratory's 12.5 km QuikSCAT (QSCAT) wind product (Dunbar et al. 2006) is used to analyze wind and vorticity fields over the eastern North Pacific. SeaWinds on QSCAT was a Ku-band scatterometer that provided surface vector wind data from 19 July 1999 to 23 November 2009. It had an 1800-km-wide, single swath and a repeat period of approximately 4 days (Huddleston and Spencer 2001), providing approximately twice-daily coverage at a given location (Fig. 3). The actual sampling pattern is less regular (Schlax et al. 2001), particularly at the latitudes of the Central American gaps. Data in the wind product include time, latitude, longitude, surface wind speed (10 m equivalent neutral; Kara et al. 2008), wind direction, and a rain flag.

Fig. 3. Example of daily coverage by QSCAT (M. A. Bourassa, personal communication, 2010).

To investigate the impact of the gap winds on tropical cyclogenesis, it is first necessary to identify when the gap wind events occurred. For gap winds to be present there must be enhanced northerly winds over the Gulf of Tehuantepec or enhanced easterly winds over the Gulf of Papagayo that create a surface wind jet with a fanlike pattern. These gap wind events are

categorized based on the peak wind speed in the jet. The weakest gap wind events identified have a peak wind speed in the jet of 6 m/s. There are four categories of gap wind strengths developed beginning at 6 m/s and binned in 2 m/s intervals (Fig. 4). A weak gap wind event is one in which peak winds in the jet are greater than or equal to 6 m/s and less than 8 m/s. A moderate gap wind event has peak winds greater than or equal to 8 m/s and less than 10 m/s. If the gap wind event has peak winds greater than or equal to 10 m/s and less than 12 m/s it is categorized as strong. Finally, a very strong gap wind event is defined as having peak winds greater than or equal to 12 m/s.

Fig. 4. Examples of a weak (top left) and a moderate (top right) gap wind event over the Gulf of Papagayo and a strong (bottom left) and a very strong (bottom right) gap wind event over the Gulf of Tehuantepec.

QSCAT coverage exists for the Gulf of Papagayo for about 70% or 1,052 of the 1,498 days in this study whereas the QSCAT coverage of the Gulf of Tehuantepec is significantly better at about 97% (1,447 days). Table 1 summarizes the number of gap wind events that occurred over the Gulf of Papagayo and the Gulf of Tehuantepec during the months of May through November for the period of 2002–2008 for each category of gap wind strength. This table shows that the gap winds are present over the Gulf of Papagayo for about 55% of the QSCAT coverage days and over the Gulf of Tehuantepec for about 52% of the QSCAT coverage days. The majority of the gap wind events fall within the strong or very strong categories for the Gulf of Tehuantepec whereas the majority of events for the Gulf of Papagayo fall within the moderate and strong categories. Previous studies have developed climatologies (Brennan et al. 2010; Cobb et al. 2002) for gale force (34 kt) or stronger gap wind events for the Gulf of Tehuantepec, events that primarily occur during the winter months. Therefore, the summary of gap wind events developed for this study provides insight into the summer gap winds in this region.

Table 1. Gap wind summary for May–November of 2002–2008. The columns give the number of days each category of wind strength is observed for each gap and the total number of days (percentage of days) having QSCAT coverage for each gap.

	Gulf of Papagayo	Gulf of Tehuantepec
No Gap Wind Days	474	689
Weak Gap Wind Days	72	33
Moderate Gap Wind Days	211	93
Strong Gap Wind Days	266	329
Very Strong Gap Wind Days	29	303
Total Gap Wind Days	578	758
Total Coverage Days	1052 (70%)	1447 (97%)

CHAPTER THREE

TRACK DISTURBANCES

Storm track information for this study is obtained from two sources. Dvorak fix locations, based on the Dvorak (1984) technique, for all named tropical cyclones, disturbances, and invests for each hurricane season in the eastern North Pacific basin from 2002 through 2008 are retrieved from the Dvorak Fix Archive (Cossuth et al. 2012). Unique system ID code, tropical cyclone name, fix latitude, fix longitude, fix time, hours prior to cyclogenesis, and Dvorak current intensity number (Dvorak 1984) are among the variables included in these data. Dvorak fix locations are often available prior to classification by the National Hurricane Center (NHC), which aids in tracking the disturbances. The Dvorak fix locations for 2004 Hurricane Celia and 2006 Hurricane John are given in Fig. 5. The second source of track information is TC reports from the NHC. The TC reports contain information on the development of the TCs along with the times at which any sort of disturbance, such as an easterly wave, may have crossed the Central American Mountains and led to the development of the storm (NHC 2002–2008).

Fig. 5. Dvorak fix locations for 2004 Hurricane Celia beginning at 0000 UTC 18 July 2004, and 2006 Hurricane John beginning at 0000 UTC 25 August 2006. The letter L indicates the location where each storm became a depression. Locations where they became tropical storms and hurricanes are denoted by their respective symbols.

With the information provided by the Dvorak Fix Archive and the NHC TC reports, it is possible to track the disturbances between QSCAT overpasses using Gridded Satellite (GridSAT) Infrared (IR) data to track the cloud clusters. The GridSAT IR data, a composite product of IR data from global geostationary satellites (Knapp et al. 2011), is provided by the

National Climatic Data Center (NCDC). The dataset has 8-km spatial grid spacing and 3-hour temporal spacing. Tracking the cloud clusters allows for the timing and location of the disturbance to be confirmed in the QSCAT surface vorticity plots. Using the tracks of the disturbances, the TC reports, and the GridSAT IR data make it possible to locate and track the precursor disturbances with a good degree of confidence.

The GridSAT IR imagery shows the propagation of the disturbances that develop into 2004 Hurricane Celia and 2006 Hurricane John (Fig. 6). Hurricane Celia was classified as a tropical depression at 0000 UTC on 19 July 2004. Using the Dvorak fix locations and the GridSAT IR imagery, the disturbance that developed into Celia is tracked back to Central America where it emerged in the EPAC on 11 July 2004. Hurricane John was classified by the NHC as a tropical depression at 0000 UTC on 28 August 2006. Dvorak fix locations begin at 0000 UTC on 25 August 2006. Examination of the GridSAT IR imagery reveals that the disturbance that developed into John entered the EPAC on 24 August 2006.

After determining the time that the disturbances are near each of the gaps, it is possible to observe whether gap winds are present. An overpass by QSCAT at 1100 UTC on 11 July 2004, (Fig. 7), as Hurricane Celia was entering the EPAC near the Gulf of Papagayo, reveals that strong gap winds are present over the Gulf of Papagayo. There is also an overpass by QSCAT at 1200 UTC on 13 July 2004 (Fig. 7) when Celia's disturbance is to the south of the Gulf of Tehuantepec. This overpass shows the presence of very strong gap winds over the Gulf of Tehuantepec. Rain contamination is present to the south of the Tehuantepec gap wind jet, which is identified by the presence of the very strong across swath wind vectors. Although a rain flag is included in the QSCAT wind product (Dunbar et al. 2006) and implemented in this study, the flag does not always identify all of the rain contaminated vectors. This rain contamination is one of the drawbacks to using QSCAT winds and must be taken into consideration when looking at the vorticity computed from the wind vectors. For Hurricane John, an overpass by QSCAT at 1200 UTC on 24 August 2006 (Fig. 7) shows that moderate gap winds are present over the Gulf of Papagayo and very strong westerly winds are present to the south. In chapter 7, evidence is provided that these westerly winds are due to the presence of the monsoon trough. Also, there were no gap winds present over the Gulf of Tehuantepec as John passed by on 27 August 2006.

Fig. 6. GridSAT IR imagery showing the progression of the disturbances that develop into 2004 Hurricane Celia (top two rows) and 2006 Hurricane John (bottom two rows). Red circles indicate the location of the disturbances at each time shown. White dots indicate the Dvorak fix location of the disturbances for times that fix locations exist.

Fig. 7. Plots of wind vectors displaying the gap wind events that influenced the development of 2004 Hurricane Celia (left and middle) at 12.5 km grid spacing and 2006 Hurricane John (right) at 37.5 km grid spacing.

CHAPTER FOUR

VORTICITY

For this study we are ignoring the diabatic and baroclinic vorticity generation mechanisms and focusing on the adiabatic and barotropic mechanisms through which the gap winds generate vorticity. There are three general mechanisms (Fig. 8) by which the structure of the gap winds can generate vorticity. The first mechanism is through horizontal shear. The strength of the gap winds and their fanlike pattern create a shear in the surface wind field. For the northern hemisphere (NH), if the jet is oriented as shown in Fig. 8, positive or cyclonic vorticity is generated on the eastern side of the jet and negative or anticyclonic vorticity is created on the western side. The second way that the gap winds can generate vorticity is through the addition of curvature in the jet. If the jet curves to the east as in Fig. 8, in the NH the positive vorticity on the eastern side of the jet is enhanced while the negative vorticity on the western side is slightly reduced. Finally, the presence of westerly winds due to the monsoon trough south of the gap wind jet can also enhance the positive vorticity on the southern side of the jet in the NH as displayed in Fig. 8. If the jet is also curved while the monsoon trough is present, this vorticity can be enhanced even more.

Fig. 8. Vorticity mechanisms for the gap wind jets. Black arrows indicate wind vectors. Red circular arrows with a plus sign in the middle indicate regions of positive vorticity and blue circular arrows with a negative sign in the middle indicate regions of negative vorticity for the NH.

Once the gap wind events are identified, plots of area-averaged surface relative vorticity are created from the QSCAT winds. The vorticity calculation is adapted from the work of Bourassa and McBeth-Ford (2010). This calculation uses the circulation theorem to compute the circulation around a “shape,” which is then divided by the area of the shape to give the area-averaged relative vorticity at the center of the shape. The shape used for the area averaging is dependent upon the diameter chosen, which is a multiple of the distance between adjacent wind vectors (12.5 km). A shape with a diameter of 12.5 km will be a square and a shape with a diameter of 25 km will be a diamond. The shape will become more circular as the diameter increases (Fig. 9). As the shape becomes more circular the random error is reduced in the vorticity calculation. A diameter of 125 km is used in this study to decrease the amount of noise present in the vorticity plots while still allowing the vorticity associated with the disturbances to be tracked. In calculating the circulation about the shape, a spline fit is used to interpolate between adjacent good wind vectors. This is a slight improvement to the calculation of Bourassa and McBeth-Ford (2010) who used a linear interpolation. Also, if there are too many points (<20%; Bourassa and McBeth-Ford 2010) missing around the circumference of the shape, the vorticity is set to missing.

Fig. 9. Shapes for diameters of 12.5 km (left), 25 km (middle left), 37.5 km (middle right), and 50 km (right) (Bourassa and McBeth-Ford 2010). The bold lines show the perimeter of the shape.

Surface vorticity calculated from the QSCAT overpass of 2004 Hurricane Celia’s disturbance at 1100 UTC on 11 July 2004 shows that the gap winds over the Gulf of Papagayo generate a region of positive vorticity that is subsequently tracked in the QSCAT overpasses (Fig. 10). Even with the presence of rain contamination near the Tehuantepec gap wind jet at 1200 UTC on 13 July 2004, positive vorticity generated by the gap winds is observed (Fig. 10). This vorticity created by the Tehuantepec gap winds appears to then propagate toward the disturbance and add to its surface vorticity. For 2006 Hurricane John, the surface vorticity

calculated from the QSCAT overpass at 1200 UTC on 24 August 2006 reveals that significant positive vorticity is present on the south side of the Gulf of Papagayo gap wind jet (Fig. 10). The contrast between the easterly Papagayo gap wind jet and the westerly winds to the south amplifies the amount and strength of positive surface vorticity generated by the gap winds. This initial vorticity is tracked as the disturbance develops into Hurricane John (Fig. 10).

Fig. 10. Swaths of surface vorticity from QSCAT showing the progression of the surface vorticity that is tracked as the disturbances develop into 2004 Hurricane Celia (top two rows) and 2006 Hurricane John (bottom two rows). Reds indicate positive vorticity and blues indicate negative vorticity. The spatial region for each panel is 0-25°N and 70-120°W. Black circles indicate the location of the disturbances based on the GridSAT IR imagery whereas black dots indicate the Dvorak fix location of the disturbance for times that fix locations are available.

CHAPTER FIVE

VERIFICATION OF QSCAT VORTICITY USING CCMP

Because of the limited temporal coverage of the disturbances by QSCAT, the CCMP ocean surface wind data record is used for verification to confirm the propagation of the surface vorticity seen in the QSCAT overpasses. CCMP combines cross-calibrated wind speeds from three microwave radiometer sensors, cross-calibrated wind speeds and directions from two scatterometers, and ship and buoy wind data with background winds from ECMWF to produce an ocean surface wind (10 m) data record on a 0.25° latitude–longitude grid (Atlas et al. 2011). This dataset has 6-hour temporal spacing, which allows for tracking the propagation of the vorticity in between overpasses of the disturbances by QSCAT.

Latitude-averaged ($7\text{--}17^\circ\text{N}$) Hovmöller diagrams of CCMP vorticity are created to observe whether the vorticity is propagating with the disturbances. These Hovmöller diagrams have longitude on the x -axis and time, increasing from bottom to top, on the y -axis. Regions of positive vorticity oriented from lower right to upper left indicate that the positive vorticity is propagating from east to west. The vorticity for the disturbance that developed into 2004 Hurricane Celia can be tracked in the Hovmöller diagram of CCMP latitude-averaged vorticity (Fig. 11). This Hovmöller diagram further suggests that the vorticity generated by the Papagayo gap winds on 11 July 2004 and by the Tehuantepec gap winds on 13 July 2004 contributed to Celia's surface vorticity. A noteworthy feature on this Hovmöller diagram is that the dipole of vorticity generated by the Tehuantepec gap winds on 13 July 2004 is seen as a disruption in the propagation of the positive vorticity. However, this is only because of the strength and spatial extent of the negative vorticity produced by the gap winds compared to the positive vorticity associated with the disturbance. For 2006 Hurricane John, the Hovmöller diagram of CCMP latitude-averaged vorticity (Fig. 11) also confirms that the vorticity created by the Papagayo gap wind jet on 24 August 2006, propagates with the disturbance as it develops. This diagram also shows that some positive vorticity was present near the longitude of the Gulf of Papagayo on 23 August 2006. This vorticity is not as significant as that present on 24 August 2006, and there is no coverage of the region by QSCAT on the 23rd to verify either the source or the magnitude of this vorticity.

Fig. 11. Hovmöller diagram of CCMP vorticity averaged over 7–17°N from 10 July 2004 through 19 July 2004 for 2004 Hurricane Celia (left) and from 23 August 2006 through 30 August 30 for 2006 Hurricane John (right). Vertical black lines denote the longitudes of the Gulf of Tehuantepec and the Gulf of Papagayo. The black lines beginning at 18 July 2004 and 25 August 25 show Dvorak fix locations for Celia and John, respectively.

CHAPTER SIX

GAP WIND CONTRIBUTIONS

To quantify the contributions of the Papagayo and Tehuantepec gap winds to the development of each of the systems investigated in this study, three contribution categories are developed. The gap winds are said to make a large contribution to the development of the disturbance (1) if they produce cyclonic vorticity that appears to provide the main source of vorticity for the initial disturbance or (2) if the gap winds are present with westerly winds to their south creating the main source of vorticity (Fig. 12). A medium contribution occurs if the gap winds appear to produce vorticity that contributes to the initial disturbance along with another significant source not associated with the gap winds (Fig. 12). Finally, the gap winds are categorized as making a small contribution to the development if they appear to contribute vorticity to an existing region of positive vorticity after development begins (Fig. 12).

Fig. 12. Sample QSCAT vorticity plots indicating a large contribution from Gulf of Papagayo gap winds (left), medium contribution from Gulf of Papagayo gap winds (middle), and a small contribution from Gulf of Tehuantepec gap winds (right). Reds indicate positive vorticity and blues indicate negative vorticity.

For 2004 Hurricane Celia, there is no other initial source of positive vorticity, other than that produced by the Papagayo gap winds, when the disturbance first entered the EPAC. Therefore, it is determined that the gap winds over the Gulf of Papagayo make a large contribution to the development of Hurricane Celia. The gap winds over the Gulf of Tehuantepec create vorticity that contributes to the development of Celia after the initial surface vorticity is generated and thus make a small contribution. In the case of 2006 Hurricane John, the Hovmöller diagram of CCMP vorticity averaged over 7–17°N (Fig. 11) confirms that the initial

vorticity generated by the Papagayo gap winds and the westerly winds develops into John. Therefore, the Gulf of Papagayo gap wind event is determined to make a large contribution to the development of Hurricane John.

Table 2 gives the number of systems (TCs and invests) that have small, medium, large, or no contribution from the gap winds over the Gulf of Papagayo and Gulf of Tehuantepec for each year in this study. Overall, the Gulf of Papagayo (Gulf of Tehuantepec) gap winds contributed to the surface vorticity of 84 (43) of the 191 storm systems investigated. The majority of the systems with contributions from the gap winds over the Gulf of Papagayo fall within the medium and large contribution categories whereas the majority of contributions from the Gulf of Tehuantepec gap winds fall within the small contribution category. Over the seven years included in this study, 107 (148) systems had no contribution from the Papagayo (Tehuantepec) gap winds. Included in these 107 (148) systems are those in which no gap winds are present and those for which coverage by QSCAT is insufficient to determine whether gap winds are present during development.

Table 2. Summary of the number of systems (TCs and invests) to which gap winds over the Gulf of Papagayo (Gulf of Tehuantepec) make small, medium, large, or no contribution to their development, for each year in this study. The total number of storms for each year along with the total number of storms that had small, medium, large, or no contribution by the gap winds is also shown.

Year	Low	Medium	High	None	Total Storms
2002	2 (8)	9 (2)	3 (0)	12 (16)	26
2003	3 (4)	5 (1)	7 (2)	19 (27)	34
2004	2 (5)	10 (1)	3 (1)	14 (22)	29
2005	1 (6)	7 (0)	3 (0)	14 (19)	25
2006	0 (3)	10 (2)	4 (0)	17 (26)	31
2007	1 (1)	3 (0)	3 (0)	13 (19)	20
2008	0 (4)	7 (3)	1 (0)	18 (19)	26
Total	9 (31)	51 (9)	24 (3)	107 (148)	191

CHAPTER SEVEN

MONSOON TROUGH AND ITCZ INTERACTIONS

As discussed in chapter 6, the Gulf of Papagayo and Gulf of Tehuantepec gap winds contribute to surface vorticity as disturbances develop into invests or TCs. However, the presence of gap winds alone is not a sufficient indicator of whether a disturbance will develop. Gap winds are present over both gulfs for more than 50% of the QSCAT coverage days investigated, but invests and TCs do not occur every time these gap winds are observed. To gain a better understanding of the gap winds' role in the development of the systems, their contributions are evaluated in terms of coincidence with the monsoon trough and the ITCZ. Figure 13 shows a general schematic of the ITCZ and the monsoon trough. The ITCZ occurs when the northeast trade winds from the NH converge with the southeast trade winds from the southern hemisphere (SH) whereas the monsoon trough occurs because of a convergence of the NH northeast trades and the monsoon southwesterlies.

Fig. 13. Generalized illustration of the wind patterns that create the ITCZ (left) and the monsoon trough (right).

To observe when the monsoon trough or ITCZ is present, longitude-averaged Hovmöller diagrams of the CCMP zonal wind component are examined. These plots average the zonal wind component from 80–140°W; latitude is on the x -axis and time, increasing from bottom to top, is on the y -axis. Positive values indicate that westerly winds are the dominant zonal wind direction and negative values indicate that easterly winds are dominant. Strong westerly winds indicate that the monsoon trough is present whereas weak westerlies or easterlies indicate the

ITCZ is more prominent. Latitude positions of the storm tracks are then plotted over the Hovmöller diagrams to compare the presence of the monsoon trough or the ITCZ with storm occurrences and the contribution that the gap winds make to the development of each storm. The dates when gap winds are present are also plotted on these diagrams for comparison. The Hovmöller diagram of longitude-averaged CCMP zonal wind component for August 2006 (Fig. 14) suggests that the westerly winds observed south of the Papagayo gap wind event on 24 August 2006, are associated with the presence of the monsoon trough. The CCMP longitude-averaged zonal wind Hovmöller diagram for September 2006 is also shown in Figure 14. These diagrams show that the majority of the storms that occurred during August and September 2006 developed while the monsoon trough was present.

Fig. 14. Hovmöller diagram of CCMP zonal wind averaged over 80–140°W for August 2006 (left) and September 2006 (right). Vertical black lines denote the latitudes of the Gulf of Papagayo and Gulf of Tehuantepec and thick black line segments indicate the presence of gap winds over each gulf. The green line beginning at 25 August 2006 shows Dvorak fix latitudes for 2006 Hurricane John while the gray lines indicate the Dvorak fix latitudes of other TCs that developed during August and September 2006. Blues indicate westerly winds and reds indicate easterly winds.

A summary of the number of TCs that have contributions from the Gulf of Papagayo and the Gulf of Tehuantepec gap winds while (1) strong westerly winds (monsoon trough) are present or (2) weak westerly or easterly winds (ITCZ) are present is given in Table 3. A total of

118 TCs occurred over the 7 years of this study, and 98 of these TCs occurred while the monsoon trough was present. The Gulf of Papagayo gap winds contribute to 44 of these 98 TCs and the Gulf of Tehuantepec gap winds contribute to 20. It is hypothesized that the proximity and alignment of the Gulf of Papagayo with the monsoon trough is the main reason that the Gulf of Papagayo gap winds contribute to significantly more TCs when the monsoon trough is present compared to the Gulf of Tehuantepec gap winds. When the westerlies are weak or the ITCZ becomes more prominent, only 20 TCs are observed. Gulf of Papagayo gap winds contribute to the development of 14 of these storms and Gulf of Tehuantepec gap winds contribute to 9.

Table 3. Summary of the number of TCs that occurred while strong westerlies (monsoon trough) were present or weak westerlies or easterlies (ITCZ) were present along with the contribution from the Gulf of Papagayo (Gulf of Tehuantepec) gap winds.

	No Gap Wind	Gap Wind & No Contribution	Small Contribution	Medium Contribution	Large Contribution	Total
Strong Westerlies	47 (47)	7 (31)	4 (13)	25 (6)	15 (1)	98
Weak Westerlies or Easterlies	4 (7)	2 (4)	2 (8)	9 (1)	3 (0)	20
Total	51 (54)	9 (35)	6 (21)	34 (7)	18 (1)	118

CHAPTER EIGHT

CONCLUSION

This study provides an insight into the summer gap winds over the Gulf of Papagayo and the Gulf of Tehuantepec. It is found that gap winds occur for more than 50% of the QSCAT coverage days for both gaps. These gap winds are also found to generate positive surface relative vorticity that appears to contribute to the formation of TCs in the EPAC. Gap winds over the Gulf of Papagayo contribute to approximately 44% (49%) of the storm systems (TCs) investigated and the Gulf of Tehuantepec gap winds contribute to approximately 23% (25%) of the storm systems (TCs) investigated. The majority of the storms with contributions from the Papagayo gap winds fall within the medium or high contribution categories whereas the majority of the contributions by the Tehuantepec gap winds fall in the low contribution category. Additionally, the location at which a system is classified as a TC is not an indication of whether gap winds may have contributed to the development of the disturbance.

The larger influence of the gap winds over the Gulf of Papagayo is a new result that has not been observed in the EPAC prior to this study. Previous studies have focused on the influence that Tehuantepec gap winds have on cyclogenesis in this region and not on the influence Papagayo gap winds have. The proximity and alignment of the Papagayo gap winds to the monsoon trough westerlies is the most likely reason that they appear to have a larger influence on cyclogenesis in the EPAC. Approximately 76% (44/58) of the TCs with contributions from the Papagayo gap winds occurred while the monsoon trough was present and approximately 69% (20/29) of the TCs with contributions from the gap winds over the Gulf of Tehuantepec occurred while the monsoon trough was present. Only 20 out of 118 TCs formed when the westerly winds were weak or when the ITCZ was present. This suggests that the presence of the monsoon trough creates a much more favorable environment for cyclogenesis and that vorticity generated by the gap winds appears to make the environment even more favorable for development. However, it should be noted that the presence of the gap winds themselves is not sufficient for cyclogenesis to occur because gap winds are present far more often than cyclogenesis occurs.

Although the gap winds appear to contribute to cyclogenesis in the EPAC it is difficult to say how large this contribution is. Because of the number of storms that fall within the low and medium contribution categories, for both gap wind regions, it appears that cyclogenesis is influenced by the gap-wind-induced low-level vorticity combining with a large-scale feature such as the monsoon trough or the ITCZ. There is a great deal of research that could be conducted in the future to confirm the actual role that the gap winds play in cyclogenesis in the EPAC. Taking a more detailed look into the proximity and alignment of each of the gaps with the monsoon trough could provide more understanding as to why it appears that the Papagayo gap winds contribute more often. Also, connecting the surface vorticity with features at mid and upper levels could help to determine why the vorticity generated by the gap winds is not sufficient itself for cyclogenesis to occur.

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BIOGRAPHICAL SKETCH

Heather Holbach was born and raised in Beaver Dam, Wisconsin. As a child, she was extremely terrified of thunderstorms and tornadoes. In order to overcome her fear, she began to keep an eye on the weather forecasts so that she could be prepared for whatever weather was in store for the day. Eventually, her fear turned into a passion for meteorology. She graduated as valedictorian from Beaver Dam High School in June 2006. In the fall of 2006 she began working towards her B.S. in meteorology at Florida State University. During her senior year at FSU, she completed an Honors in the Major project with Dr. Mark Bourassa. In April 2010, Heather graduated from FSU *magna cum laude* with Honors. She decided to stay at FSU and continue working with Dr. Bourassa to pursue her M.S. degree in meteorology beginning in the fall of 2010. During the summer of 2011 she had the opportunity to intern at the Naval Research Laboratory in Monterey, California where she worked with Dr. Patricia Pauley. After completing her M.S. degree, Heather plans to continue to work with Dr. Mark Bourassa to obtain her PhD.