The ITCZ in the Central and Eastern Pacific on Synoptic Time Scales

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ABSTRACT

The ITCZ in the central and eastern Pacific on synoptic time scales is highly dynamic. The active season extends roughly from May through October. During the active season, the ITCZ continuously breaks down and re-forms, and produces a series of tropical disturbances. The life span of the ITCZ varies from several days to 3 weeks.

Sixty-five cases of ITCZ breakdown have been visually identified over five active seasons (1999–2003) in three independent datasets. ITCZ breakdown can be triggered by two mechanisms: 1) interaction with westward-propagating disturbances (WPDs) and 2) the vortex rollup (VR) mechanism. Results show that the frequency of occurrence of ITCZ breakdown from these two mechanisms is the same. The VR mechanism may have been neglected because the produced disturbances are rather weak and they may dissipate quickly. The ITCZ shows a strong tendency to re-form within 1–2 days in the same location. The ITCZ may break down via the VR mechanism without any other support, and thus it may continuously generate numerous tropical disturbances throughout the season.

There are two main differences between the two mechanisms: 1) The WPDs-induced ITCZ breakdown tends to create one or two vortices that may be of tropical depression strength. The VR-induced ITCZ breakdown generates several nearly equal-sized weak disturbances. 2) The WPDs tend to disturb the ITCZ in the eastern Pacific only. Disturbances generally move along the Mexican coast after shedding off from the ITCZ and do not further disturb the ITCZ in the central Pacific. Therefore, the VR mechanism is observed more clearly and is the dominating mechanism for ITCZ breakdown in the central Pacific.

1. Introduction

On seasonal time scales, the intertropical convergence zone (ITCZ) is thought to be a feature nearly in steady state. It is the place where the northeasterly and southeasterly trade winds converge. Air rises in deep convection, moves poleward in the upper troposphere, and sinks in the subtropics where the subtropical highs are located. The air then flows back to lower latitudes in the lower troposphere and converges into the ITCZ to complete the circulation. This closed circulation is called the "Hadley cell," and the ITCZ is its rising branch. In the western Pacific, the location of the ITCZ migrates seasonally with the sun. However, in the eastern Pacific, the ITCZ tends to stay in the Northern Hemisphere (NH) year-round. The shape of the ITCZ varies with longitude. In the western Pacific, the ITCZ is broader in latitude mainly due to the warm pool in the ocean, while in the eastern Pacific, the ITCZ is narrow and long, generally being located at the southern boundary of the eastern Pacific warm pool, north of the strongest meridional gradient of sea surface temperature (Raymond et al. 2003; Yin and Albrecht 2000).

The picture of the ITCZ is quite different on synoptic time scales (order of 10 days) from the seasonal time scale (order of 100 days). From day to day, the ITCZ is highly dynamic and changeable as seen in visible and infrared geostationary satellite images [Geostationary Operational Environmental Satellite (GOES)] that measure cloud reflectivity and cloud-top temperature, respectively (Fig. 1). It may be quite narrow (2° latitude) and stretched over 70° in longitude for a few days, developing undulations whose amplitude may increase over the next few days until the entire ITCZ breaks down into smaller disturbances, some of which may strengthen with time as they move away, while others dissipate. The ITCZ may then re-form in the original location, the entire life cycle taking on the order of 10 days. The fields of precipitation and low-level convergence are both too noisy to characterize the instantaneous ITCZ, even though both fields are used to de-

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scribe the monthly or seasonal mean ITCZ. We find that low-level vorticity describes the ITCZ well in instantaneous data. It shows up as a narrow strip of positive vorticity near the surface [in Quick Scatterometer (QuikSCAT) data] or at 975 hPa [in National Centers for Environmental Prediction (NCEP) data].

Deep and shallow ITCZs are considered in our investigation. Shallow convection or shallow Hadley cell has been observed in several independent datasets (e.g., Zhang et al. 2004). Its rising branch is in the ITCZ as for the conventional Hadley cell, but its divergent outflow lies just above the top of the planetary boundary layer. The strength and depth of a shallow ITCZ changes seasonally. It is strongest and deepest in fall/winter at about 3-km height, and shallowest in spring at about 1-km height. Murakami et al. (1992) and Zhang et al. (2004) suggest that the shallow convection is most robust when deep convection is absent. In GOES satellite images, the shallow ITCZ is detected in visible images but not in the infrared ones, whereas the deep ITCZ shows up both in visible and infrared satellite images.

An example of ITCZ breakdown from September 2000 is shown in Fig. 1, which shows visible and infrared GOES images from the tropical Pacific. On 19 September ITCZ convection was shallow, with an easterly wave appearing on the right edge of the image, which did not disturb the ITCZ but just moved northwestward along the coast. The ITCZ intensified into a deep ITCZ 2 days later (21 September) and started undulating from its western end. The ITCZ broke into three pieces on 23 September (due to the vortex rollup mechanism that will be described in the following paragraph). The produced disturbances were rather weak and not well organized. They moved toward high latitudes and dissipated. On 29 September, an ITCZ re-formed in the same region around 10°N.

ITCZ breakdown events can be triggered by interactions with westward-propagating disturbances (WPDs), which include easterly waves that originated over the Atlantic (e.g., Avila and Clark 1989, and references therein) and tropical disturbances that may have been excited by flow going over the Central American mountains (e.g., Zehnder and Powell 1999, and references therein). ITCZ breakdown may also occur due to local instability of the heating-induced, lower-tropospheric, vorticity strip (Charney 1963; Hack et al. 1989; Schubert et al. 1991, Guinn and Schubert 1993; Nieto Ferreira and Schubert 1997; Wang and Magnusdottir 2005), which is called the vortex rollup (VR) mechanism in this paper. Nieto Ferreira and Schubert (1997) simulated the VR mechanism in shallow-water (barotropic) simulations in a background state of rest. Wang and Magnusdottir (2005) simulated the mechanism for both shallow and deep ITCZ breakdown in a fully three-dimensional dynamical model and examined the effect of various background flows. The VR mechanism is suggested to be an efficient mechanism to pool vorticity in the tropical atmosphere, which represents the early stage of cyclogenesis.

An easterly wave in the tropical east Pacific may be traced as far back as the Atlantic basin using 700-hPa meridional wind perturbations (or surface pressure) and can be distinguished from the locally generated disturbances. However, both types are considered disturbances external to the ITCZ in the central and eastern Pacific. In a series of modeling studies by Schubert and collaborators (Hack et al. 1989; Schubert et al. 1991; Guinn and Schubert 1993; Nieto Ferreira and Schubert 1997) and in Wang and Magnusdottir (2005), the term "ITCZ breakdown" was used for the events specifically triggered by the VR mechanism. In this paper, we name the mechanism "the vortex rollup mechanism" to avoid confusion.

ITCZ breakdown has been largely ignored due to the difficulty in identifying the event in conventional measurements, especially in the tropical central to eastern Pacific where observations are sparse. This gives the impression that the observed ITCZ breakdown event (late July to early August 1988, in the central to eastern Pacific) shown in Hack et al. (1989), Schubert et al. (1991), and Nieto Ferreira and Schubert (1997) was an isolated event, which it was not. The difficulty is mainly associated with horizontal resolution of observational products. The horizontal resolution of conventional reanalysis data (2.5° × 2.5°) is not fine enough to depict ITCZ breakdown events. We have analyzed NCEP reanalysis data (2.5° × 2.5°) and did not locate any ITCZ breakdown events. In our modeling study (Wang and Magnusdottir 2005), we found that a horizontal resolution of at least 1.1° × 1.1° was required in a primitive equation model to produce strong horizontal wind shear to allow the VR mechanism to be initiated and to resolve the vorticity filaments. In addition, in data-poor regions, such as the tropical central to eastern Pacific, reanalysis data are often polluted by model assumptions. With the high-quality remote sensing datasets, such as QuikSCAT winds, supplemented by older satellite datasets, we are able to study the process of ITCZ breakdown in the real atmosphere. Wang and Magnusdottir (2005) assumed that ITCZ breakdown occurs in summer and fall, coincident with the hurricane season. Here, we examine the entire year to confirm the extent of the active season for ITCZ breakdown. We then focus on the active seasons in 1999–2003. The goals of this study are the following:

1) to identify occurrences of ITCZ breakdown north of the equator in the central to eastern Pacific, and
2) to classify the triggering mechanism of each ITCZ breakdown event, using satellite cloud images and other datasets (see section 2).

The central to eastern Pacific is the area most likely for ITCZ breakdown to occur. The narrower the ITCZ and the farther that it is located away from the equator, the more readily it will break down due to the VR mechanism since the narrower ITCZ has stronger meridional wind shear and the Coriolis effect is stronger the higher the latitude. This shape of ITCZ is most likely to occur in the central to eastern Pacific, and in summer/fall it is located at about 10°N. Observational studies have shown that during the hurricane season, tropical disturbances are particularly active in the area (e.g., Molinari et al. 1997; Molinari and Vollaro 2000; Maloney and Hartmann 2000a,b; Gu and Zhang 2001). These tropical disturbances, which include westward-propagating synoptic-scale disturbances as well as disturbances associated with the Madden–Julian oscillation (MJO), may influence ITCZ breakdown. One is also most likely to observe the VR mechanism clearly in the central to eastern Pacific because the area is less overwhelmed by African easterly waves than the Atlantic basin and the Caribbean Sea. As we discussed previously, in the western Pacific, the ITCZ is broader and less well defined than in the central to eastern Pacific.

This paper is organized as follows: section 2 describes the datasets. Section 3 explains the methodology we used in this study. Section 4 shows the results. Sections 5 and 6 contain a discussion of the results and the conclusions.

2. Datasets

We use three independent datasets to identify ITCZ breakdown events. Each dataset has its own advantages and disadvantages. Thus, it is necessary to combine different resources.

1) *GOES-West visible (VS) and infrared images (IR):* Daily GOES VS images [approximately at 1830 coordinated universal time (UTC[1])] and twice-daily IR images (approximately at 0000 and 1230 UTC) are available from 14 December 1996 to 12 July 2004 on the National Climatic Data Center (NCDC) Historical GOES Browse Server (http://cdo.ncdc.noaa.gov/GOESBrowser/goesbrowser). The time period of analysis is the entire year from 1999 to 2003. *GOES-West* is centered at 135°W at the equator and covers the central and eastern Pacific. The brightness of VS images indicates the albedo, which can be used to infer the depth of the cloud. The thicker the cloud, the higher the albedo. For IR images, the brightness indicates the temperature of cloud top, which can be used to infer the height of cloud top. Therefore, a deep convective system would be bright white on both IR and VS images while a shallow convective system would be dark on IR and white on VS images. Combining VS and IR images, one can deduce whether the ITCZ is shallow or deep. Usually, a cloud shown only on VS images has its cloud top not far above the top of the planetary boundary layer and can be identified as a shallow ITCZ.
2) *NCEP global tropospheric analyses:* This dataset is of $1° \times 1°$ horizontal resolution, has 26 vertical levels, and is recorded 4 times per day. It is available for the time period from September 1999 to the present. The relative vorticity on pressure levels is computed and used to locate the ITCZ and the produced disturbances, as well as to monitor the increase in vorticity value while vorticity is pooling in time. We focus on relative vorticity at 975 hPa in order to compare it to the surface vorticity field from QuikSCAT. Potential vorticity (PV) at 310-K isentropic surface shows the same evolution of the ITCZ. However, at this level, the shallow ITCZ is often not described as well as by relative vorticity at 975 hPa. The disadvantage of this dataset is that it contains model assumptions that sometimes affect the accuracy of the data. However, this dataset is the most comprehensive of its kind and is of high resolution.
3) *QuikSCAT scatterometer wind:* This dataset is of $0.25° \times 0.25°$ resolution with two scans (ascending and descending) per day from September 1999 to the present. It covers nearly 93% of the ocean surface on the globe. The 10-m wind is derived from surface roughness, approximately equivalent to an 8–10-min mean surface wind with an accuracy of 2 m s^{-1} in wind speed and an accuracy of 20° in wind direction. In situ studies (e.g., Bourassa et al. 2003) report that the scatterometer winds are more accurate than the mission-stated objectives. Relative vorticity is calculated from the daily averaged zonal and meridional wind components. The daily average is taken when both ascending and descending scans are available at the grid point. Other grid points use the one available observation per day. Some missing values are filled in using linear interpolation in space, and a five-point Gaussian-weighted running mean is applied to reduce noise.

[1] The start time of receiving the image from the satellite. It is approximately the same as Greenwich mean time.

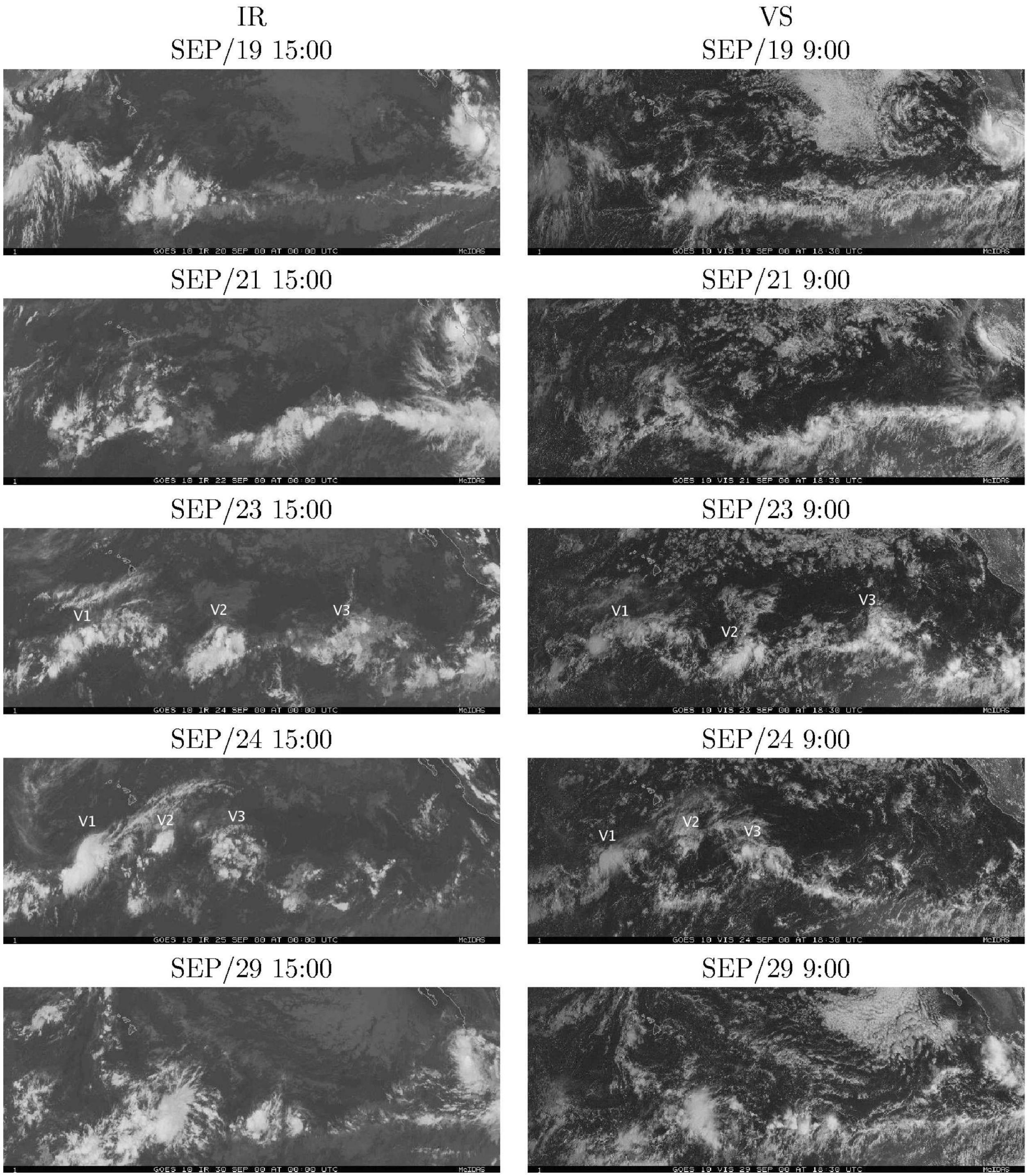

FIG. 1. ITCZ breakdown that occurred in September 2000. Domain shown here is from the equator to 25°N, 180° to 100°W. (left) IR images and (right) VS images. Dates from top to bottom are 19, 21, 23, 24, and 29 Sep. Time indicated is the local time at 135°W. Here V1, V2, and V3 indicate the produced disturbances from breakdown.

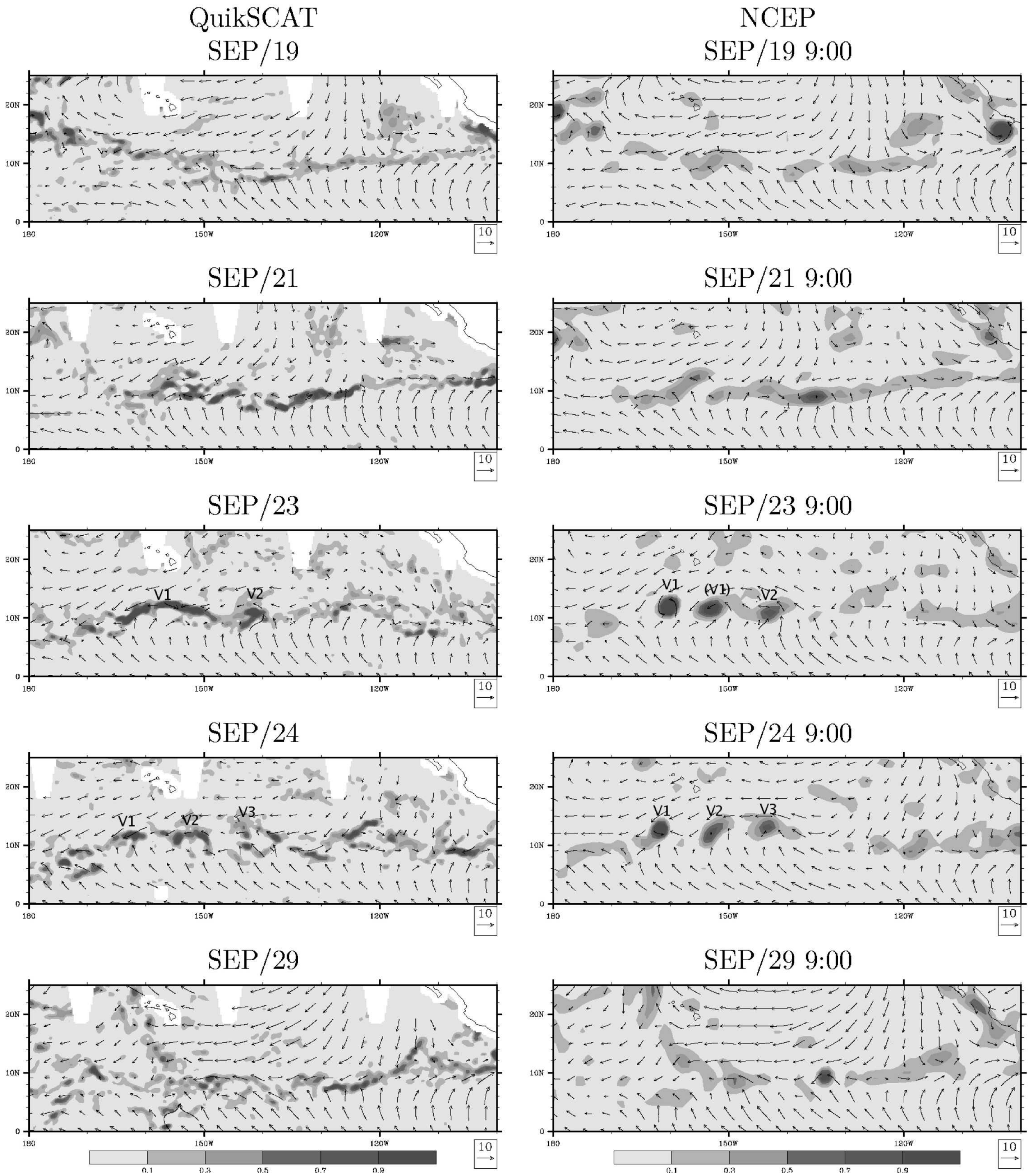

FIG. 2. The wind (vector) and vorticity (shaded) fields corresponding to Fig. 1. (left) QuikSCAT daily surface vorticity and wind fields. (right) NCEP vorticity and wind at 975 hPa. Dates from top to bottom are 19, 21, 23, 24, and 29 Sep. Time indicated is the local time at 135°W. The unit of wind vector is m s^{-1}. Grayscale interval is 0.2×10^{-5} s^{-1}. White areas in QuikSCAT are missing values. Here V1, V2, and V3 indicate the produced disturbances.

3. Methodology

We look through all the available datasets and visually detect ITCZ breakdown that occurred during 1999–2003. The criteria for ITCZ breakdown are as follows.

1) On satellite images, before the ITCZ breaks, an elongated cloud band must be seen on VS images, and for the deep ITCZ, it has to be detected on IR images as well. The cloud band then undulates and clouds pool in certain regions. Some of the cloud clusters may break off from the ITCZ. The evolution of ITCZ breakdown is a process that is continuous in time. Thus, the produced disturbances can be traced back to the ITCZ. See Fig. 1 for an example.
2) On plots of the near-surface vorticity field, elongated positive vorticity patches line up at a certain latitude (usually at 10°N) for both NCEP and QuikSCAT wind-derived vorticity. During breaking, vorticity is pooled in regions, and while pooling, the value of vorticity increases and the rollup should be seen in the vorticity field. We note that it is not easy to see a long and smooth vorticity strip in the NCEP analyzed vorticity field at 6-h interval at 975 hPa. Instead, we usually see a few elongated high-vorticity areas as shown in Fig. 2.

All ITCZ breakdown events are catalogued into three types according to the dynamical mechanism that triggered the event. The three types are breakdown due to VR, WPDs, and mix of the two mechanisms (VR + WPDs). The mixed type means that the two mechanisms take place in two different regions of the ITCZ: WPDs-induced breakdown usually takes place in the eastern Pacific, and the VR mechanism in the central Pacific.

To further classify the ITCZ by convection depth, three subtypes are listed: shallow, deep, and shallow plus deep. "Shallow" means an ITCZ breakdown event with cloud tops near the top of the boundary. "Deep" means an ITCZ breakdown event with cloud tops in the upper troposphere. Cases that have shallow ITCZ with some elements of deep convection within it are defined as shallow plus deep. The height of convection in each event may be estimated since the cloud-top temperature is available from IR images.

The temporal and spatial scales of disturbances produced by the VR and WPDs mechanisms are thought to be similar (Nieto Ferreira and Schubert 1997). Hence, the best way to distinguish between these two mechanisms is to trace the locations and origins of WPDs.

4. Results

The tropical disturbances have a strong annual cycle. After examining the *GOES-West* images throughout the annual cycle from 1999 to 2003 (inclusive), we have found that ITCZ breakdown events occur almost exclusively during May to October, which is referred to as the active season. November to April will be referred to as the inactive season. Three examples will be shown in this section.

a. Inactive season

During the inactive season, sequences of southwest–northeast-oriented cloud bands were observed quite frequently in the central and eastern Pacific. These extratropical systems are called cold surges and have been shown to interact with the ITCZ in the eastern Pacific and Atlantic basins in many observational studies (e.g., Kiladis and Weickmann 1992, and references therein). The extratropical cold air, which can be characterized by the typical frontal cloud and cloud street from satellite images, moves toward the equator, often accompanied by a cold front and midlatitude cyclone. Once the cold air reaches the Tropics and meets the warm and moist tropical air, tropical convection is initiated. This tropical convection connects to the frontal cloud band to form a system that extends from the tropical convergence zone northeast into the midlatitudes. Some studies call the enhanced tropical convection "plumes." The system propagates eastward with the midlatitude cyclone. The cold front moves eastward but the tropical plume tends to stay in place. This causes the system to eventually separate and leave the isolated tropical convection behind. Because of this effect, wintertime tropical convection acts very differently from its summertime counterpart. During the inactive season, other convection in the Tropics seems to be greatly suppressed. Even if there is an ITCZ present, it is mostly due to a shallow, narrow, and weak convergence zone. The tropical plumes can be coherent within the shallow ITCZ, but they are not what we classify as ITCZ convection. Almost all the shallow ITCZs in the inactive season from 1999 to 2003 eventually dissipated without breaking.

b. Active season

The active season of ITCZ breakdown is from May to October. We have identified 65 cases of ITCZ breakdown during the 1999–2003 active seasons. As listed in Table 1, 27 events were due to the VR mechanism, another 27 events were due to WPDs, 10 events were due to the combined effects of both mechanisms, and 1

TABLE 1. Number and type of different ITCZ breakdown cases by year.

	VR	WPDs	Both	Not classified	Total
1999	6	5	3	0	14
2000	6	7	1	1	15
2001	4	3	3	0	10
2002	4	5	2	0	11
2003	7	7	1	0	15
	27	27	10	1	65

event could not be classified. If catalogued by the depth of convection (Table 2), there are 38 events of deep ITCZ breakdown, 12 events of shallow ITCZ breakdown, and 15 events of shallow-plus-deep ITCZ breakdown. The elements of deep convection within the shallow ITCZ produce an uneven vorticity distribution in the ITCZ. The local maxima often become the centers of the vortices after the ITCZ has broken down, but the breakdown process is not accelerated. Detailed information on all 65 cases is listed in Table 3. From the list, we can see that ITCZ breakdown events occur quite often during the active season.

Three examples of ITCZ breakdown are shown in this paper. They are typical examples of VR-triggered, VR plus WPD triggered, and WPD-triggered events.

An example of an ITCZ breakdown case due to the VR mechanism is shown in Figs. 1 and 2. This was a case of shallow ITCZ breakdown that occurred at the end of September 2000. The shallow ITCZ can be seen only on the VS image on 19 September (Fig. 1). Both NCEP and QuikSCAT vorticity fields show positive vorticity maxima near the surface at the same time (Fig. 2). The ITCZ undulated in the following 3 days (21–23 September), and the intensity increased when the vorticity strip started to pool in several regions on 23 September. The ITCZ rolled up into three vortices on 23 September, labeled as V1, V2, and V3. The number of disturbances is determined by the width of the ITCZ (e.g., Joly and Thorpe 1990). As shown in GOES images and QuikSCAT data, V1 was a loose banana-shaped disturbance. However, it was interpreted as two separate vortices, labeled as V1 and (V1), in NCEP analysis. None of the disturbances developed into a named tropical storm. A new shallow ITCZ started forming around 100°–145°W on 26 September (not shown) and reached its maximum strength on 29 September.

Figures 3 and 4 show an example of ITCZ breakdown due to the combination of the two mechanisms. This case occurred in early September 2001. After the previous ITCZ dissipated, the new ITCZ formed on 1 September. Two strong WPDs (V1 and V2) were seen at the eastern edge of the region. The vorticity strip west of V1 intensified (shown in QuikSCAT and NCEP, 3 September) and possibly started to pool in several regions due to the VR mechanism on 5 September. Although the disturbances were hard to distinguish on satellite images, the QuikSCAT vorticity field showed three bumps (labeled as D1, D2, and D3) that were the signature of vortex rollup in this region. These disturbances dissipated and seemed to reconnect during 6–10 September according to the vorticity field. Vortices V1 and V2 developed into two hurricanes, Gil (4–9 September) and Henriette (4–8 September), and broke off from the ITCZ on 8 September. Hurricanes Gill and Henriette merged and then dissipated to a weak vortex as shown in the vorticity field later (around 10 and 11 September).

The WPD-only case is shown in Figs. 5 and 6. This case occurred during 17–31 August 2002. An elongated cloud band with a few gaps could be seen on 18 August in the GOES images. We classify it as an ITCZ, based on the QuikSCAT and NCEP vorticity, which show an elongated structure. A WPD (V1) was observed at 135°W on 21 August, and V2 was a rather loose disturbance at 120°W. A tropical depression, F, moved across Central America on 17 August and intensified into Hurricane Fausto later (21 August–3 September). The appearance of Hurricane Fausto significantly distorted V2. We could see some development of V2 on August 23 in GOES images and QuikSCAT. Then, as Hurricane Fausto approached, V2 was stretched and started to merge into Fausto. The hurricane later shed off from V2 and moved toward high latitude on 26 August. During 28–29 August, V1 and the remaining part of V2 dissipated and the new ITCZ re-formed during 30–31 August (not shown).

During the active season, the ITCZ has a strong tendency to re-form in the same location following breakdown. The new convergence zone may reappear as fast as in a few days. This is consistent with the results of Hack et al. (1989) that suggested that diabatic heating may induce a strong vorticity anomaly within 1–2 days. For some extreme cases, the new ITCZ forms just a few degrees latitude south of the ITCZ-produced distur-

TABLE 2. Depth of ITCZ for breakdown events by year.

	Shallow	Deep	Both	Total
1999	5	7	2	14
2000	3	7	5	15
2001	0	6	4	10
2002	0	11	0	11
2003	4	7	4	15
	12	38	15	65

TABLE 3. List of date and type of occurrence of ITCZ breakdown in 1999–2003. The "VR" means vortex rollup, "WPDs" means westward-propagating disturbances, and "VR + WPDs" means the triggering factors involve both mechanisms; "deep" means deep ITCZ, "shallow" means shallow ITCZ, and "shallow + deep" means shallow ITCZ with some deep convection in it. The "remarks" column lists tropical cyclones that developed from that event. Named tropical cyclones have reached hurricane intensity, unless otherwise indicated. The "TS" means tropical storm; "TD" means tropical depression.

Case No.	Period	Type	Remarks
1	31 May–8 Jun 1999	VR, deep	
2	14–21 Jun 1999	WPDs, deep	Adrian
3	23 Jun–2 Jul 1999	VR, shallow	
4	13–28 Jul 1999	VR + WPDs, deep	TS Calvin
5	30 Jul–4 Aug 1999	VR, deep	
6	5–11 Aug 1999	WPDs, shallow + deep	Dora and Eugene
7	11–21 Aug 1999	WPDs, shallow	TS Fernanda
8	25 Aug–10 Sep 1999	VR + WPDs, shallow	Greg
9	13–16 Sep 1999	VR, deep	11, 12 missing
10	18–20 Sep 1999	VR + WPDs, shallow	Hilary
11	21–25 Sep 1999	VR, deep	
12	29 Sep–6 Oct 1999	VR, shallow	
13	8–15 Oct 1999	WPDs, shallow + deep	TS Irwin
14	20–30 Oct 1999	WPDs, deep	
15	25–30 Apr 2000	VR, deep	
16	3–13 May 2000	Not classified, deep	
17	14–30 May 2000	WPDs, shallow + deep	Aletta
18	9–19 Jun 2000	WPDs, shallow + deep	TS Bud
19	20–25 Jun 2000	WPDs, shallow + deep	Carlotta
20	27 Jun–2 Jul 2000	VR, shallow	
21	10–19 Jul 2000	VR, deep	
22	22–27 Jul 2000	WPDs, deep	Daniel and Emilia
23	31 Jul–12 Aug 2000	WPDs, shallow + deep	Fabio and Gilma
24	10–17 Aug 2000	WPDs, shallow	Ileana
25	19 Aug–3 Sep 2000	VR, deep	TS John and TS Kristy
26	7–14 Sep 2000	WPDs, deep	Lane
27	19–26 Sep 2000	VR, shallow	
28	29 Sep–13 Oct 2000	VR + WPDs, shallow + deep	Olivia
29	22–29 Oct 2000	VR, deep	TS Paul
30	25 May–1 Jun 2001	VR + WPD, shallow + deep	Adolph
31	12–30 Jun 2001	WPD, deep	TS Barbara
32	1–12 Jul 2001	VR, shallow + deep	
33	14–27 Jul 2001	WPDs, shallow + deep	TS Cosme
34	4–9 Aug 2001	VR, deep	
35	17–25 Aug 2001	VR, deep	
36	1–12 Sep 2001	VR + WPDs, deep	Gil, Henriette
37	19–27 Sep 2001	VR, deep	
38	25 Sep–3 Oct 2001	WPDs, shallow + deep	Juliette
39	12–31 Oct 2001	VR + WPDs, deep	
40	16–20 May 2002	VP, deep	
41	21 May–5 Jun 2002	VR + WPDs, deep	Alma
42	7–17 Jun 2002	VR + WPDs, deep	TS Boris
43	23–27 Jun 2002	VR, deep	
44	11–20 Jul 2002	WPDs, deep	Cristina, Douglas, Elida
45	2–11 Aug 2002	WPDs, deep	
46	19–30 Aug 2002	WPDs, deep	Fausto, TS Genevieve
47	31 Aug–7 Sep 2002	WPDs, deep	Hernan
48	11–19 Sep 2002	WPDs, deep	Iselle
49	20 Sep–2 Oct 2002	VR, deep	
50	18–31 Oct 2002	VR, deep	Lowell, Huko (central Pacific)
51	2–5 May 2003	VR, deep	
52	8–12 May 2003	VR, deep	
53	20–25 May 2003	WPDs, deep	
54	28 May–9 Jun 2003	VR, deep	
55	30 Jun–7 Jul 2003	VR, shallow + deep	TS Dolores
56	8–15 Jul 2003	WPDs, shallow + deep	TS Enrique

TABLE 3. (*Continued*)

Case No.	Period	Type	Remarks
57	17–24 Jul 2003	WPDs, shallow	TS Felicia
58	24–31 Jul 2003	VR, shallow + deep	
59	5–16 Aug 2003	VR + WPDs, deep	TD One_c, TS Guilermo, and TS Hilda
60	22 Aug–1 Sep 2003	VR, deep	Jimena
61	1–9 Sep 2003	WPDs, deep	TS Kevin
62	15–28 Sep 2003	WPDs, shallow + deep	Linda and Marty
63	28 Sep–5 Oct 2003	WPDs, shallow	
64	10 Oct–16 Oct 2003	VR, shallow	
65	19 Oct–27 Oct 2003	WPDs, shallow	Patricia

bances, or the disturbed ITCZ before it dissipates. For instance, Fig. 7 depicts a set of VS images taken on 7–10 August 2000. These images show the formation of the new ITCZ in the eastern Pacific, extending from the right edge of the image (marked by the white dashed line). The previous ITCZ, dissipating south of Hawaii, was disturbed by a series of WPDs, and this event generated two hurricanes, Fabio (labeled as F) and Gilma (labeled as G). Hurricane Hector (labeled as H) moved into this region later, but did not disturb the new ITCZ. The life span of an entire cycle of ITCZ breakdown varies from several days (less than a week) to about 3 weeks. This time span is consistent with modeling results (Wang and Magnusdottir 2005). The breakdown proceeds similarly for both deep and shallow ITCZs. However, a shallow ITCZ will produce much weaker disturbances that may dissipate faster than disturbances produced from a deep ITCZ breakdown.

5. Discussion

a. Differences between VR- and WPDs-induced ITCZ breakdown

We have identified 65 cases of ITCZ breakdown in 1999–2003. Although the number of ITCZ breakdown events induced by the VR mechanism is the same as that triggered by WPDs, most of the latter cases (WPDs-triggered events) produced named tropical storms. More than two-thirds of those events produced disturbances that reached hurricane level. By contrast, less than one-quarter of the VR-induced events produced named tropical storms. This discrepancy can be explained in part by two different characteristics:

1) *Size:* The disturbances produced from an individual ITCZ breakdown event due to the VR mechanism are usually all about the same size. However, the disturbances produced from the WPDs mechanism are always unequal in size, with one or two larger disturbances near the Central American coast and smaller ones in the central Pacific. This is because the WPDs moving into the tropical eastern Pacific are well-developed disturbances (intensity and size) compared to the local disturbances in that region. The unequal size and intensity of the disturbances gives the larger ones a better chance of distorting and "collecting" the smaller disturbances (e.g., Ritchie and Holland 1993, and references therein) while intensifying as they propagate westward. Therefore, although these two mechanisms lead to about the same number of ITCZ breakdown events, there are more named tropical cyclones generated by the WPDs mechanism.
2) *Location:* The eastern Pacific is a potentially more unstable region than the central Pacific (e.g., Beven and Franklin 2004). The ITCZ is observed to re-form in the eastern Pacific as quickly as in a day. The WPDs propagate into the tropical eastern Pacific in sequence. They disturb the ITCZ and vortices break off from its easternmost end. The vortices tend to move northwestward along the Mexican coast often without disturbing the western part of the ITCZ. It appears that easterly waves can be greatly intensified in the deep tropical eastern Pacific where they may move toward high latitudes quickly, allowing the ITCZ in this region to re-form in 1–2 days and be disturbed by the next WPD. On the other hand, disturbances produced by the VR mechanism in the western Pacific tend to linger in the Tropics longer and delay the formation of a new ITCZ.

It may appear that the contribution of easterly waves to the formation of tropical disturbances is more important than that of the VR mechanism because easterly waves do create more numerous (and stronger) named tropical cyclones (Lawrence et al. 2001; Avila et al. 2003; Franklin et al. 2003; Beven and Franklin 2004). However, for moisture transport out of the Tropics, both mechanisms are important. The VR mechanism creates numerous small disturbances. Even though only

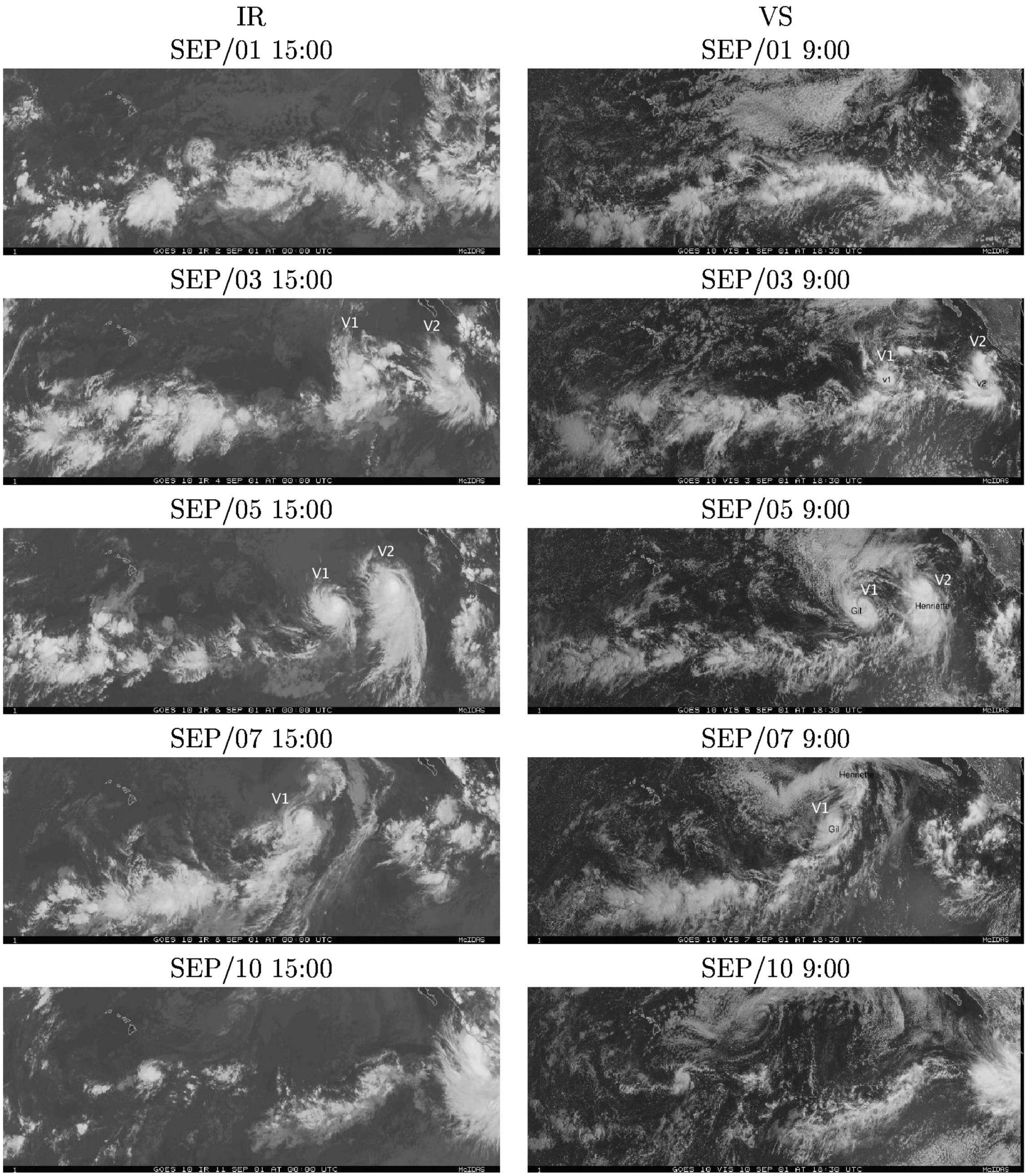

FIG. 3. The same as Fig. 1, but for the example of ITCZ breakdown due to the combination of the two mechanisms in early September 2001. The eastern Pacific was influenced by a series of WPDs, and two named hurricanes (V1 and V2) were produced while the central Pacific was dominated by the VR mechanism. The vorticity was greatly increased in the central Pacific region, although no named tropical cyclones were formed in this region.

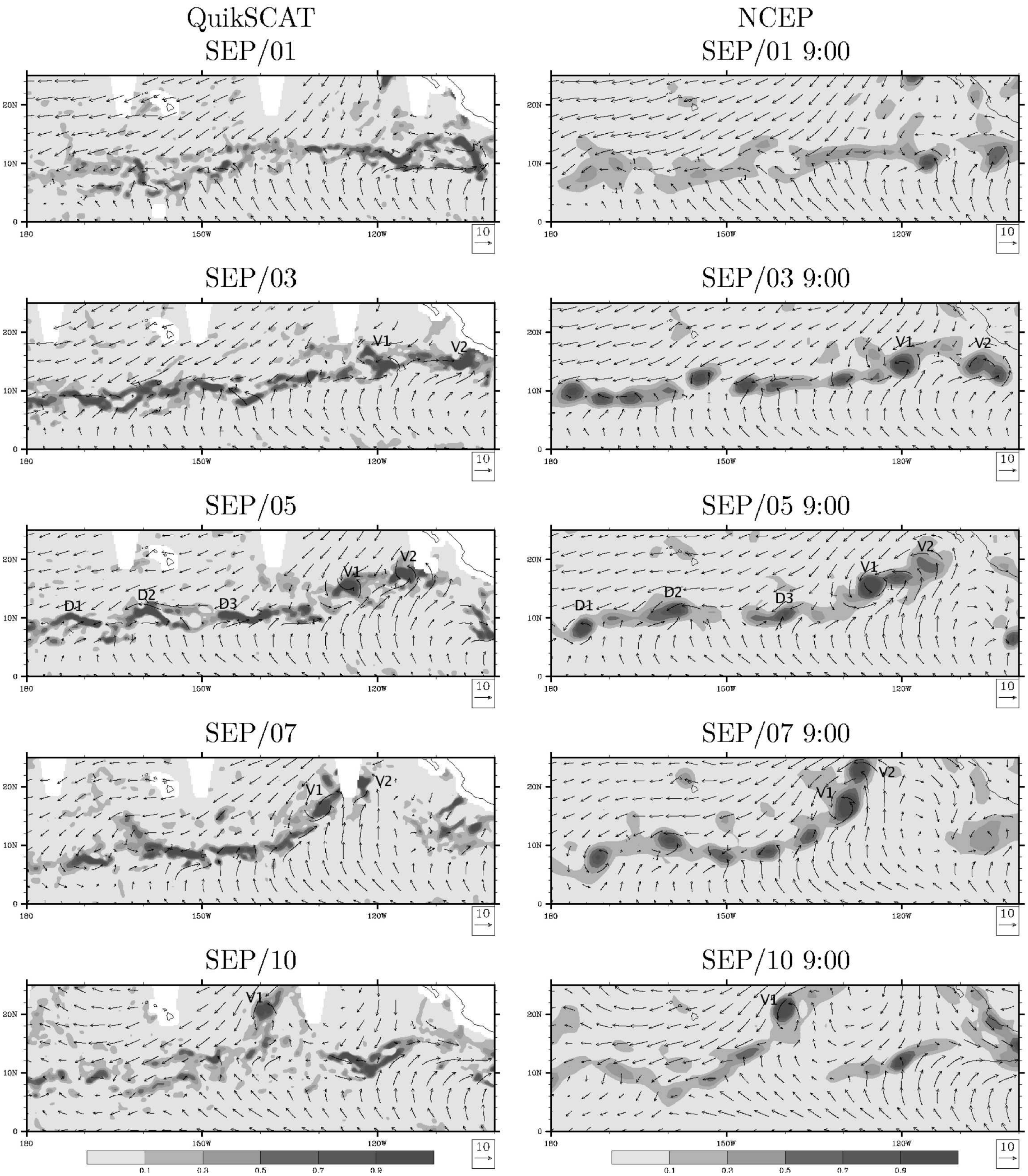

FIG. 4. The wind (vector) and vorticity (shaded) fields corresponding to Fig. 3. (left) QuikSCAT daily surface vorticity and wind fields. (right) NCEP vorticity and wind at 975 hPa. Time indicated is the local time at 135°W. The unit of wind vector is m s^{-1}. Grayscale interval is 0.2×10^{-5} s^{-1}. White areas in QuikSCAT are missing values. Here V1, V2, and D1–D3 indicate the produced disturbances.

a few of the disturbances developed into named tropical cyclones, the other disturbances still moved toward high latitudes and they may play an important role in transporting moisture poleward. Both modeling and observational results show that ITCZ breakdown due to the VR mechanism generates tropical disturbances fairly efficiently and continuously. Once a heating-induced vorticity strip, representing the ITCZ, is

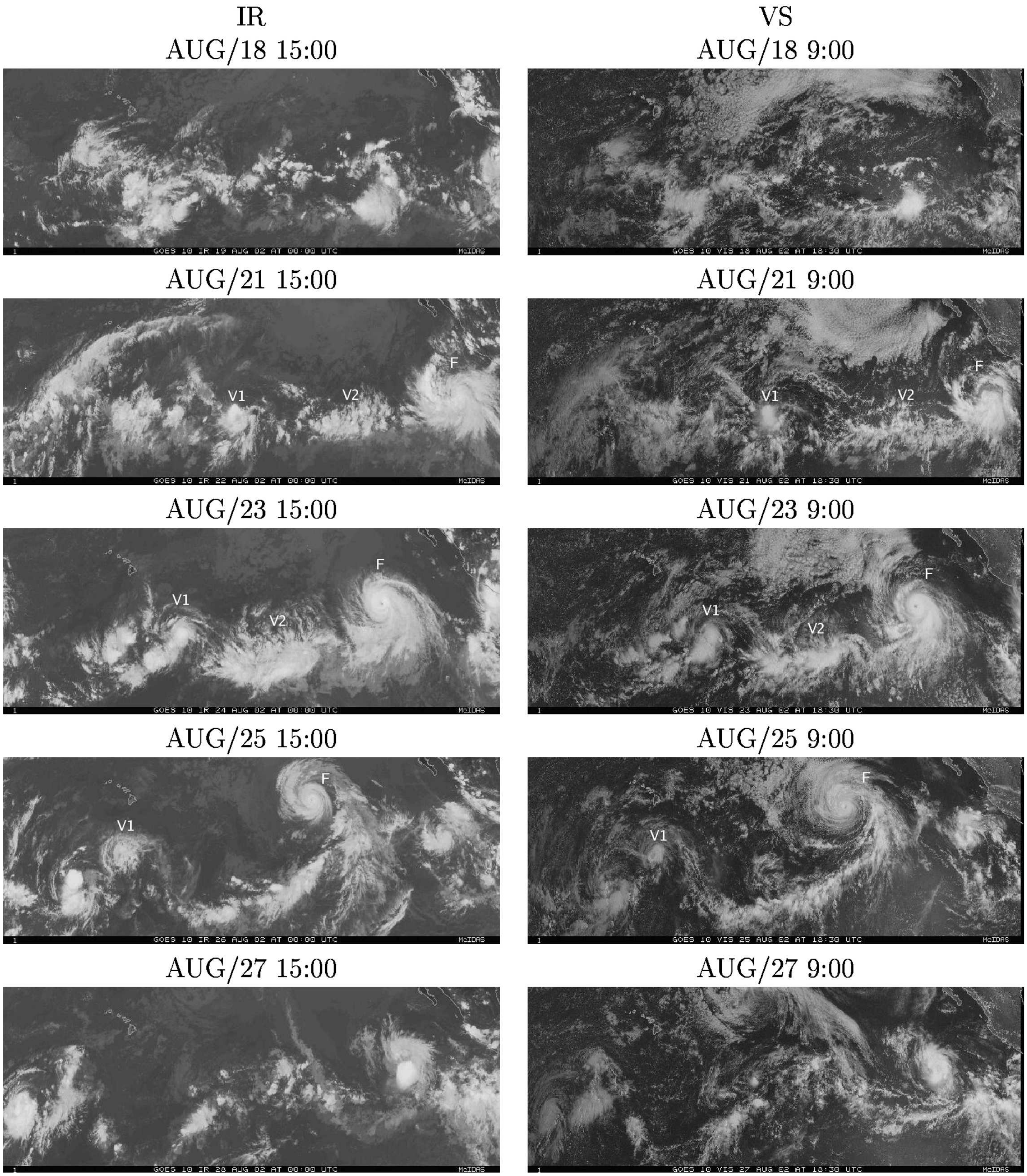

FIG. 5. The same as Fig. 1, but for a case of ITCZ breakdown triggered by WPDs. (left) The IR and (right) VS images on 18, 21, 23, 25, and 27 Aug 2002 from top to bottom. Here V1, V2, and F indicate the produced disturbances and Hurricane Fausto.

present in the tropical atmosphere, the flow satisfies the necessary conditions for combined barotropic/baroclinic instability. The ITCZ will therefore undulate and break down by itself, leaving a series of tropical disturbances.

b. The influence of MJO

A frequently asked question is that of the influence of MJO on ITCZ breakdown. Although there is no direct evidence that shows that the MJO triggers ITCZ

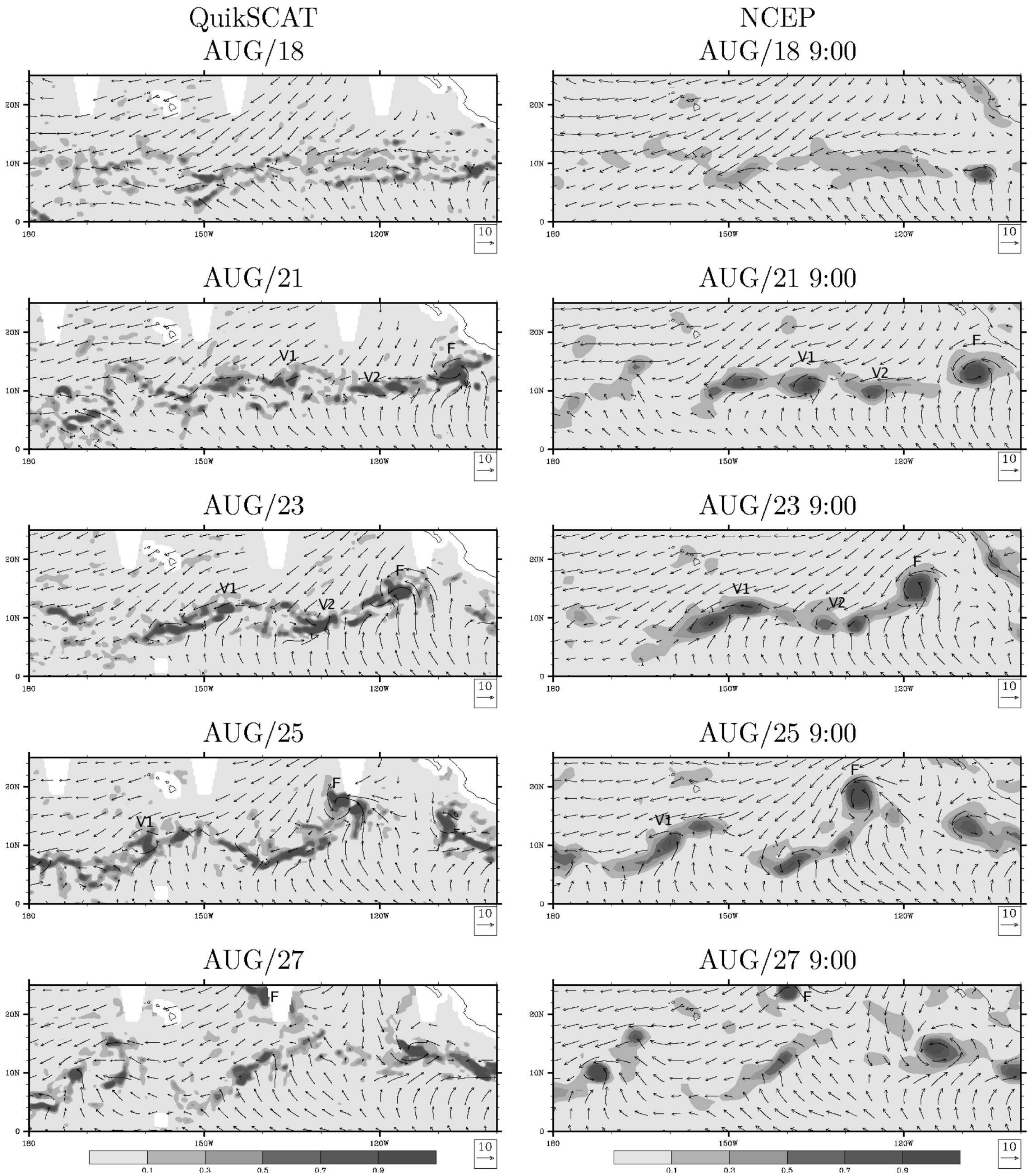

FIG. 6. The wind (vector) and vorticity (shaded) fields corresponding to Fig. 5. (left) QuikSCAT daily surface vorticity and wind fields. (right) NCEP vorticity and wind at 975 hPa. Time indicated is the local time at 135°W. The unit of wind vector is m s^{-1}. Grayscale interval is 0.2×10^{-5} s^{-1}. White areas in QuikSCAT are missing values. Here V1, V2, and F indicate the produced disturbances and Hurricane Fausto.

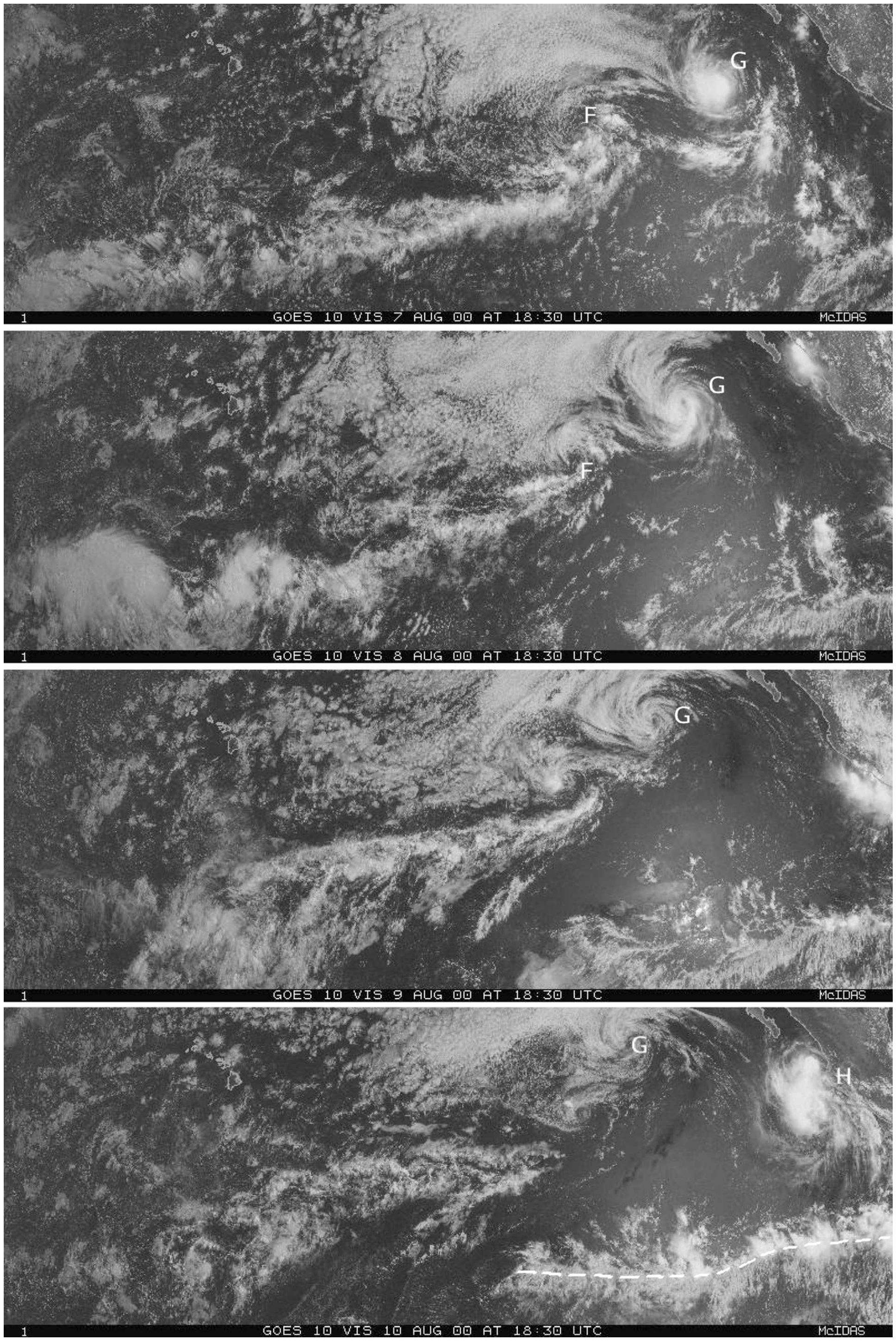

FIG. 7. The VS images taken on 7–10 Aug 2000 (from top to bottom). These images show the formation of the new ITCZ in the tropical eastern Pacific, extending from the right edge of the image to the west (marked by the white dashed line). The previous ITCZ was disturbed by a series of WPDs and generated two hurricanes, Fabio (labeled as F) and Gilma (labeled as G). The cloud band south of Hawaii is the remnant of the previous ITCZ that dissipated; H is another WPD moving into this region.

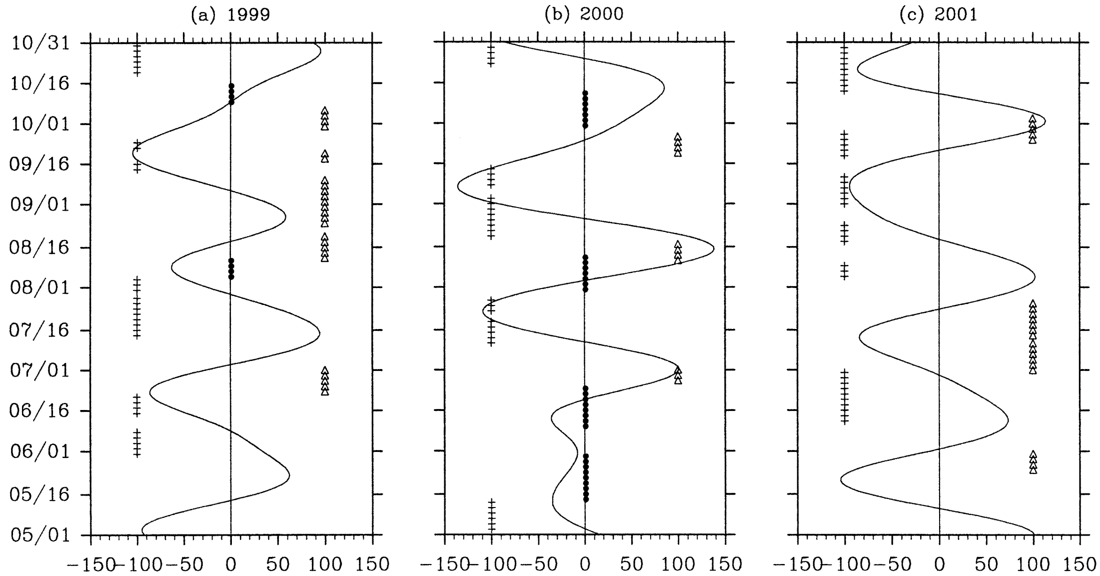

FIG. 8. The relation between ITCZ convection depth and the MJO for (a) 1999, (b) 2000, and (c) 2001. The *x* axis is the MJO index of 1999–2001 defined by Maloney and Kiehl (2002). The *y* axis is the date from 1 May to 31 Oct. Negative (positive) value means westerly (easterly) phase in the eastern Pacific and corresponds to enhanced (suppressed) convection. Plus (+) symbol indicates deep ITCZ breakdown events. Solid dot (●) indicates shallow + deep events, and open triangle indicates (Δ) shallow events.

breakdown, several studies have shown that the MJO may have a strong influence on cyclogenesis, or at least may provide conditions favorable to it (Maloney and Hartmann 2000a,b). We compared the depth of each ITCZ breakdown event to the MJO index that is defined by Maloney and Kiehl (2002) to investigate a possible relation.

Maloney and Kiehl (2002) use the 850-hPa wind from NCEP reanalysis data (2.5° × 2.5°) to define and calculate the MJO index. Please refer to their paper for details. We plot the index for the 1999–2001 active seasons and indicate the ITCZ breakdown events (by depth) in Fig. 8. Plus symbols (+) indicate periods of deep ITCZ breakdown events, solid dots (●) indicate shallow-plus-deep cases, and open triangles (Δ) indicate shallow cases. The value of the MJO index is defined to represent the different MJO phases. The definition and the corresponding wind fields can be found in Maloney and Hartmann (1998). The maximum value of the MJO index corresponds to the phase that has strong easterlies in the lower troposphere in the eastern Pacific. It also corresponds to suppressed convection in this region. On the contrary, the minimum value of the MJO index represents the phase that has strong westerlies, indicating enhanced convection in the eastern Pacific. Figure 8b shows that during the active season in 2000, the period of deep convection corresponds to the westerly phase of the MJO during which time the atmospheric environment is changing from conditions neutral to convection to conditions of enhanced convection. The shallow-plus-deep and shallow events occurred when the MJO is changing from the westerly phase to easterly phase during which time the atmospheric environment is switching from neutral to suppressed convection. However, this relation between the MJO phase and ITCZ depth is only valid after August in 1999 and 2001 (shown in Figs. 8a and 8c). Figure 8 suggests that the depth of the ITCZ may be influenced by MJO activities. The exact nature of this influence is still an open question.

c. The problem with NCEP analysis data

We compared the GOES satellite images, QuikSCAT, and NCEP high-resolution analysis and noticed two types of inconsistence in NCEP high resolution analysis.

1) Analysis data tend to form series of vortices located in close proximity instead of an elongated vorticity strip (as shown in Fig. 2).
2) Inconsistencies in time also occur in NCEP analysis so that certain events are off in time compared to the other datasets.

For example, the intensity of Tropical Storms John and Kristy (August–September 2000; not shown) in NCEP data shows inconsistencies in the time evolution compared to the best tracking data from the National Oceanic and Atmospheric Administration (NOAA). Tropical Storm John reached its most intense level on 30 August, but it shows the strongest PV value on 28 August in NCEP data. However, for Tropical Storm Kristy, the storm reaches its maximum intensity on 3 September in NCEP data when it has decayed to a depression in the best tracking data. We conclude that the analysis data are not of as good quality as its high spatial resolution would lead one to expect.

6. Conclusions

We have found that ITCZ breakdown events occurred mostly during May to October. Sixty-five ITCZ breakdown events are visually identified in the five active seasons of 1999–2003. The VR mechanism is a robust mechanism for inducing ITCZ breakdown and produces the same number of ITCZ breakdown events as the WPDs. WPDs produce more "named" tropical cyclones because they are usually better organized than the disturbances produced from the VR mechanism.

These two mechanisms contribute to ITCZ breakdown in different ways. When a WPD enters the tropical eastern Pacific, it is either a stronger disturbance than the local tropical disturbances or it may grow into a more organized disturbance once it enters this region that is a monsoon-like environment (Beven and Franklin 2004). For the first scenario, the WPD will have a better chance of collecting other smaller disturbances around it and thereby intensify. For the second scenario, the monsoon-like environment is favorable to intensifying the disturbance. For both scenarios, the ITCZ disturbed by easterly waves will produce one or two large vortices close to the coast, which often intensify into named tropical cyclones. These vortices tend to move northwestward and break off from the ITCZ quickly, leaving an undulating ITCZ that may break down later by the VR mechanism or be disturbed by the next WPD. Producing stronger vortices along the coast is the most noticeable characteristic of the WPD cases.

We have seen several cases of ITCZ breakdown that are triggered by both mechanisms. Some of them have both mechanisms occurring at about the same time, WPDs in the eastern Pacific and the VR mechanism in the central Pacific. Some of them have one of the two mechanisms occurring first, breaking down part of the ITCZ, and another mechanism occurring a few days later, breaking up the rest of the ITCZ.

The life span of a complete vortex rollup process (from an elongated ITCZ to the newly re-formed ITCZ) is about 1–3 weeks. This means the ITCZ breakdown can be triggered by the VR mechanism and it can generate tropical disturbances every 1–3 weeks without any external disturbances.

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REFERENCES

Avila, L. A., and G. B. Clark, 1989: Atlantic tropical systems of 1988. *Mon. Wea. Rev.,* **117,** 2260–2265.

——, R. J. Pasch, J. L. Beven, J. L. Franklin, M. B. Lawrence, S. R. Stewart, and J.-G. Jiing, 2003: Eastern North Pacific hurricane season of 2001. *Mon. Wea. Rev.,* **131,** 249–262.

Beven, J. L., and J. L. Franklin, 2004: Eastern North Pacific hurricane season of 1999. *Mon. Wea. Rev.,* **132,** 1036–1047.

Bourassa, M. A., D. Legler, J. J. O'Brien, and S. R. Smith, 2003: Seawinds validation with research vessels. *J. Geophys. Res.,* **108,** 3019, doi:10.1029/2001JC001028.

Charney, J. G., 1963: A note on large-scale motions in the Tropics. *J. Atmos. Sci.,* **20,** 607–608.

Franklin, J. L., L. A. Avila, J. L. Beven, M. B. Lawrence, R. J. Pasch, and S. R. Stewart, 2003: Eastern North Pacific hurricane season of 2002. *Mon. Wea. Rev.,* **131,** 2379–2393.

Gu, G., and C. Zhang, 2001: A spectrum analysis of synoptic-scale disturbances in the ITCZ. *J. Climate,* **14,** 2725–2739.

Guinn, T. A., and W. H. Schubert, 1993: Hurricane spiral bands. *J. Atmos. Sci.,* **50,** 3380–3403.

Hack, J. J., W. H. Schubert, D. E. Stevens, and H.-C. Kuo, 1989: Response of the Hadley circulation to convective forcing in the ITCZ. *J. Atmos. Sci.,* **46,** 2957–2973.

Joly, A., and A. J. Thorpe, 1990: Frontal instability generated by tropospheric potential vorticity anomalies. *Quart. J. Roy. Meteor. Soc.,* **116,** 525–560.

Kiladis, G. N., and K. M. Weickmann, 1992: Extratropical forcing of tropical Pacific convection during northern winter. *Mon. Wea. Rev.,* **120,** 1924–1938.

Lawrence, M. B., L. A. Avila, J. L. Frankin, R. J. Pasch, and S. R. Stewart, 2001: Eastern North Pacific hurricane season of 2000. *Mon. Wea. Rev.,* **129,** 3004–3014.

Maloney, E. D., and D. L. Hartmann, 1998: Frictional moisture convergence in a composite life cycle of the Madden–Julian oscillation. *J. Climate,* **11,** 2387–2403.

——, and ——, 2000a: Modulation of hurricane activity in the Gulf of Mexico by the Madden–Julian oscillation. *Science,* **287,** 2002–2004.

——, and ——, 2000b: Modulation of eastern North Pacific hurricanes by the Madden–Julian oscillation. *J. Climate,* **13,** 1451–1460.

——, and J. T. Kiehl, 2002: MJO-related SST variations over the tropical eastern Pacific during Northern Hemisphere summer. *J. Climate,* **15,** 675–689.

Molinari, J., and D. Vollaro, 2000: Planetary- and synoptic-scale influences on eastern Pacific tropical cyclogenesis. *Mon. Wea. Rev.,* **128,** 3296–3307.

——, D. Knight, M. Dickinson, D. Vollaro, and S. Skubis, 1997: Potential vorticity, easterly waves, and eastern Pacific tropical cyclogenesis. *Mon. Wea. Rev.,* **125,** 2699–2708.

Murakami, T., B. Wang, and S. W. Lyons, 1992: Contrasts between summer monsoons over the Bay of Bengal and the eastern North Pacific. *J. Meteor. Soc. Japan,* **70,** 191–209.

Nieto Ferreira, R., and W. H. Schubert, 1997: Barotropic aspects of ITCZ breakdown. *J. Atmos. Sci.,* **54,** 261–285.

Raymond, D. J., G. B. Raga, C. S. Bretherton, J. Molinari, C. López-Carrillo, and Ž. Fuchs, 2003: Convective forcing in the intertropical convergence zone of the eastern Pacific. *J. Atmos. Sci.,* **60,** 2064–2082.

Ritchie, E. A., and G. J. Holland, 1993: On the interaction of tropical-cyclone-scale vortices. II: Discrete vortex patches. *Quart. J. Roy. Meteor. Soc.,* **119,** 1363–1379.

Schubert, W. H., P. E. Ciesielski, D. E. Stevens, and H.-C. Kuo, 1991: Potential vorticity modeling of the ITCZ and the Hadley circulation. *J. Atmos. Sci.,* **48,** 1493–1509.

Wang, C.-C., and G. Magnusdottir, 2005: ITCZ breakdown in three-dimensional flows. *J. Atmos. Sci.,* **62,** 1497–1512.

Yin, B., and B. A. Albrecht, 2000: Spatial variability of atmospheric boundary layer structure over the eastern equatorial Pacific. *J. Climate,* **13,** 1574–1592.

Zehnder, J. A., and D. M. Powell, 1999: The interaction of easterly waves, orography, and the intertropical convergence zone in the genesis of eastern Pacific tropical cyclones. *Mon. Wea. Rev.,* **127,** 1566–1585.

Zhang, C., M. McGauley, and N. A. Bond, 2004: Shallow meridional circulation in the tropical eastern Pacific. *J. Climate,* **17,** 133–139.