Description of a Monsoon Gyre and Its Effects on the Tropical Cyclones in the Western North Pacific during August 1991

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ABSTRACT

This paper describes the character and evolution of the low-level wind, sea level pressure, and satellite-observed cloudiness over the western North Pacific (WNP) during August 1991 when the low-level monsoon circulation there became organized as a monsoon gyre. The specific configuration of the monsoon circulation, which herein is called a monsoon gyre, is an episodic event—occurring roughly once per year, for two or three weeks during July, August, or September. As a monsoon gyre, the low-level circulation of the WNP becomes organized as a large cyclonic vortex associated with a nearly circular 2500-km-wide depression in the contours of the sea level pressure. A cyclonically curved band of deep convective clouds rims the southern through eastern periphery of this large vortex. Once this pattern is established, it becomes a prolific generator of mesoscale vortices that emerge from the downstream end of the major peripheral cloud band. These mesoscale vortices form the seed disturbances for midget or small-sized tropical cyclones. The large area encompassed by the outermost closed isobar of the monsoon gyre of August 1991 (the centroid of which moved slowly westward along 20°N) was the site of genesis for two tropical depressions, two tropical storms, and two typhoons during its 20-day westward journey. Initially, small tropical cyclones formed in the peripheral circulation of the gyre and later, the gyre itself evolved into a very large tropical cyclone; this is suggestive of two distinct modes of tropical cyclogenesis: one mode operates to produce small tropical cyclones in the eastern periphery of the gyre, and the other mode operates to accelerate the winds of the monsoon gyre until it becomes a giant tropical cyclone.

1. Introduction

The character and evolution of the midtropospheric subtropical ridge and the midlatitude disturbances passing by poleward of this ridge have long been used to develop the rationale for forecasts of tropical cyclone (TC) motion; these are the cited causative agents of the behavior of storms in most post analyses (e.g., Matsumoto 1984; Sandgathe 1987; JTWC[1] 1979, 1981, 1986, 1991, 1993a,b) and in forecast guides (e.g., Japanese Meteorological Agency 1976; Australian Bureau of Meteorology 1978; and the World Meteorological Organization 1993a). During the course of a basic research program to improve the understanding of tropical cyclone motion, which began during October 1986 under the sponsorship of the United States Office of Naval Research (ONR),[2] it became apparent that bi-nary interaction (Brand 1970; Dong and Neumann 1983; Lander and Holland 1993), the effects of the large-scale monsoon circulation (Harr and Elsberry 1991), and the behavior of the subtropical ridge were having a significant influence upon the motion, structure, and structure change of TCs in the western North Pacific (WNP) basin. These three factors contributed to large errors in the numerical and operational track forecasts.

The monsoon gyre of August 1991 was associated with the genesis of six TCs. One of these was a midget typhoon and another was a giant typhoon.[3] The formation, motion, and structure of the TCs associated with the monsoon gyre of August 1991 were clearly affected by the gyre circulation; section 4 is devoted to a discussion of the monsoon gyre and its relation to TC genesis, motion, and structure. The action of the

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August 1991 monsoon gyre as a prolific tropical cyclone generator, and the large size differences among the TCs spawned within its circulation, prompted the writing of this paper.

This paper focuses on a specific configuration of the low-level monsoon circulation observed during August 1991 and introduces, and explains, the use of the term "gyre" as a descriptor for this particular circulation pattern. The term, monsoon gyre, originated with this author as a label for a specific pattern of the low-level monsoon flow that dominated the WNP during August 1991. Use of it has recently spread into the tropical cyclone research and forecasting community (e.g., JTWC 1993a,b; Harr et al. 1993; WMO 1993a,b). In this wider usage, monsoon gyre has been applied to any very large low-level cyclonic vortex in the tropical WNP that is separable from TCs that are embedded within it, and that has effects upon the motion of these TCs. Some researchers (e.g., see Carr and Elsberry 1994; JTWC 1993b) have used the term "monsoon cyclone" to describe what herein we will call a monsoon gyre. In this paper, the characteristics ascribed to a monsoon gyre are more restrictive than those that have come to be widely accepted. Under the stricter criteria used herein, monsoon gyres formed in the WNP during August 1991 and again during July 1993. A description of the August 1991 monsoon gyre and of its effects upon TCs is the main content of this paper (sections 4 and 5). The July 1993 monsoon gyre is briefly described in section 6 and serves to test the conceptual model of a monsoon gyre as developed from the 1991 case. Section 7 summarizes the findings.

2. Data sources

The evolution of the low-level wind, sea level pressure (SLP) and the deep convective clouds associated with the August 1991 monsoon gyre were carefully documented using the following data sources:

1) the hand-plotted surface synoptic charts plotted operationally at the Joint Typhoon Warning Center (JTWC), Guam, which contain: sea level pressure and winds reported from ships, land stations, and drifting buoys; cloud-drift winds; and gradient-level wind reports from available upper-air stations;

2) high-resolution visible and infrared satellite imagery accessible at the JTWC;

3) the Navy's operational numerical analyses of sea level pressure and other data fields (e.g., 500-hPa height contours); and

4) the annual tropical cyclone reports (ATCR) issued by the JTWC.

The JTWC surface charts were subjectively reanalyzed by this author: a streamline analysis of the wind field was performed in addition to a contour analysis of the surface pressure field. The subjectively analyzed SLP and sequences of satellite imagery were the primary

products used to determine the structure and the evolution of the August 1991 monsoon gyre. The same products were used to determine the structure and evolution of the July 1993 monsoon gyre (see section 6). A survey of past ATCRs and an archive of full-disc satellite imagery helped to identify some of the commonly observed patterns of the monsoon circulation of the western North Pacific.

3. The monsoon circulation as a gyre

Climatologically, in late spring, a low-pressure trough becomes established over South Asia. It extends from the deserts of Saudi Arabia, eastward across Iran, Pakistan, Afghanistan, northern India, and southern China (Sadler et al. 1987). For several months, low-level winds are drawn into this low-pressure trough until the cooling of the Asian landmass in autumn leads to a rise in pressure over land and a consequent reversal of the large-scale low-level wind. The low-pressure trough of summer is known as the monsoon trough and the accompanying southwesterly wind flow feeding into it is called the Southwest Monsoon. In winter, the winds become northeasterly and are called the Northeast Monsoon. As with many large-scale atmospheric phenomena (e.g., El Niño, 40–50 day oscillations, etc.), the attempt to generalize and standardize the definition of a monsoonal climatic regime has lead to some disparity among authors concerning the appropriate delimiting elements and a consequent disparity of opinion of what regions of the globe experience a monsoonal climate. Using Ramage's (1971) monsoon definition,[4] the monsoon region lies between 35°N and 25°S and between 30°W and 170°E.

It is universally recognized that the large-scale periodic reversal of wind currents over the Indian subcontinent and in other regions commonly acknowledged to possess a monsoonal climate (e.g., northern Australia and sub-Saharan Africa) is due to the seasonal changes in the differential heating of continents and oceans. The sharp land–sea contrast contributes to the formation of the monsoonal low-pressure trough that stretches across south Asia in summer. A similar low-pressure trough, not associated with land–sea contrast, is often found over the tropical WNP in the summer. This trough and its associated cloudiness has often been called an intertropical convergence zone (ITCZ), lumping it together with the east–west-oriented cloud band of the same name found in the central and eastern
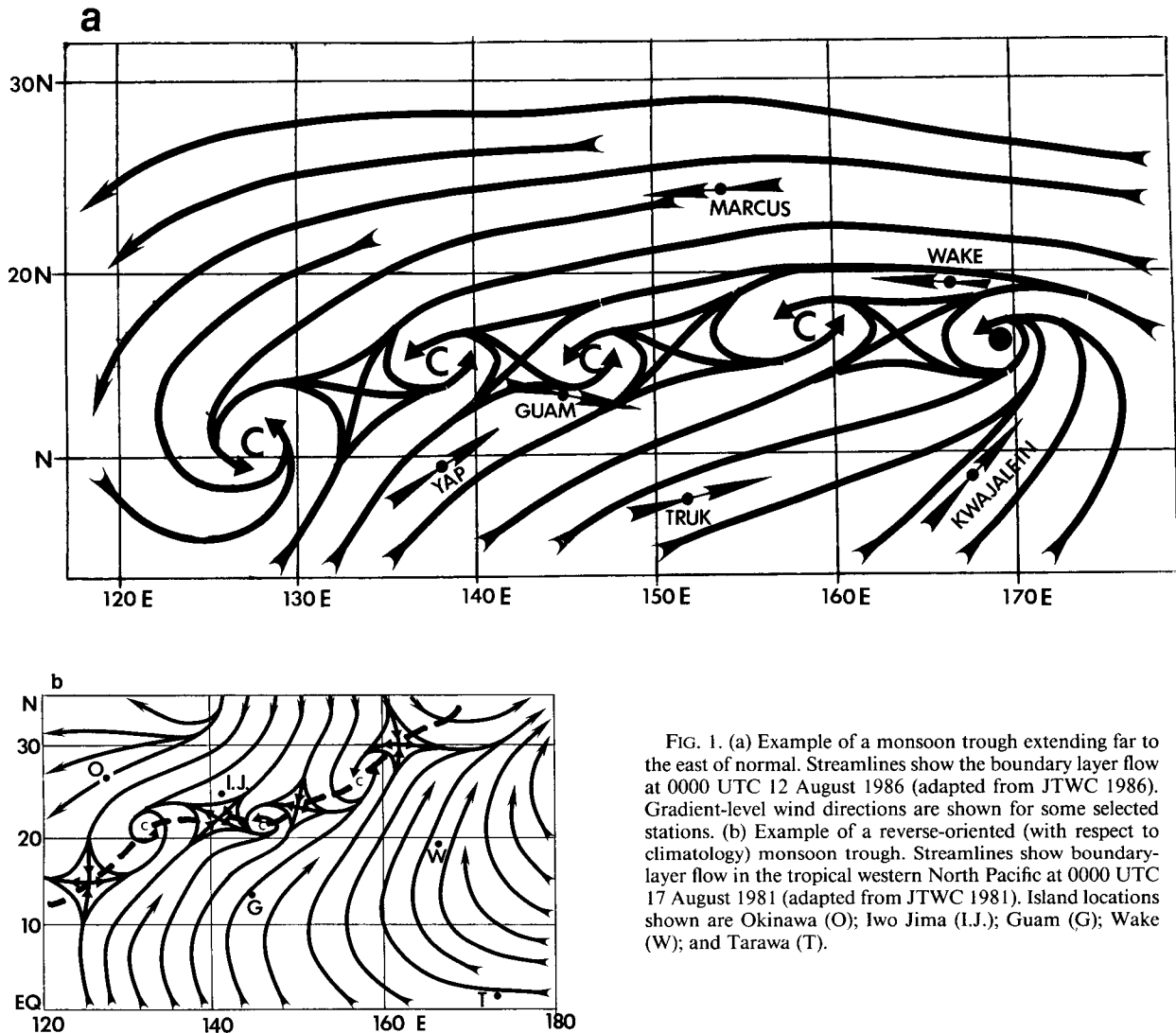
FIG. 1. (a) Example of a monsoon trough extending far to the east of normal. Streamlines show the boundary layer flow at 0000 UTC 12 August 1986 (adapted from JTWC 1986). Gradient-level wind directions are shown for some selected stations. (b) Example of a reverse-oriented (with respect to climatology) monsoon trough. Streamlines show boundary-layer flow in the tropical western North Pacific at 0000 UTC 17 August 1981 (adapted from JTWC 1981). Island locations shown are Okinawa (O); Iwo Jima (I.J.); Guam (G); Wake (W); and Tarawa (T).

North Pacific and also in the tropical Atlantic. The low-pressure trough of summer in the tropical WNP, however, has several dynamic and kinematic features that sharply distinguish it from the ITCZ of the Atlantic and eastern North Pacific (see Atkinson 1971; Sadler 1975; Sadler et al. 1987). To emphasize these differences, in particular, the presence of deep moist southwesterly wind flow to the south of the trough axis in the WNP, the low-pressure trough in the tropical WNP will herein be called a monsoon trough. In long-term averages of low-level wind flow and sea level pressure (see Sadler et al. 1987), the monsoon trough of the WNP appears to extend eastward from the South Asian low-pressure trough and is frequently accompanied by low-level southwesterly winds to the south of the trough axis. This overwater monsoon trough of the tropical WNP, though loosely anchored to the region of highest sea surface temperature, undergoes substantial migra-

tions and major changes to its shape and orientation (unlike the monsoon trough over South Asia, which is firmly anchored by topography, and unlike the ITCZs of the eastern Pacific and the Atlantic whose axes do not stray far from their mean-monthly positions). During the summer, the monsoon trough of the WNP may be found as far south as 5°N or as far north as 25°N; it may be oriented NW-SE (the orientation of the mean trough); it may stretch 2000 km along an east-west line from the Philippines to the date line (Fig. 1a); it may be found in a reverse (SW-NE) orientation (Fig. 1b); or it may not be present (as an episodic event) when easterly flow is found throughout the tropical WNP.

Most of the time, the monsoon circulation of the WNP takes the form of an elongated trough (Fig. 1). This trough marks the boundary between an easterly wind current to its north and monsoon southwesterlies

to its south. The general properties of the overwater monsoon circulation of the WNP manifested as a trough are as follows:

1) it is elongated east–west;
2) it is a nearly linear shear zone between easterly and southwesterly wind currents;
3) it possesses a nearly linear zonally oriented cloud band with most of the cloudiness and deep convective elements located to the south of the trough axis; and
4) it is the genesis site of most tropical cyclones of the western North Pacific.

A survey of the ATCRs published by the JTWC since 1960, and an examination of geostationary satellite imagery since 1979, revealed that approximately once every two years (usually during late July through early September), the low-level circulation of the tropical WNP appears as a large-scale vortex accompanying a large (2500-km mean diameter of the outermost, closed, sea level isobar) low-pressure area that is separated over water from the low-pressure over Asia by a north–south ridge of high pressure. During most of its life, a persistent band of deep convective cloud rims the southern through eastern periphery of the large low-pressure area. Herein, we will call this configuration of the monsoon circulation of the WNP a monsoon gyre. The low-pressure center of a monsoon gyre is noted by its displacement, 1000 km or more, to the north of the latitude of the long-term monthly mean axis of the monsoon trough.

Another phenomenon often associated with a monsoon gyre is the sequential genesis of very small tropical cyclones that emerge from the downstream end of its peripheral cloud band. The only previous description of a monsoon gyre (and it is incidental to his main theme) is contained in a dated paper by Arakawa (1952), wherein he investigated some very small storms of typhoon intensity, mame-taifu (literally: bean typhoon; figuratively: midget typhoon), which struck Japan. Most of Arakawa's midget typhoons were observed to originate within what he describes as a "convergence area in the subtropical latitudes." His SLP analysis for 12 August 1950 (not shown) bears a close resemblance to a SLP analysis of the August 1991 monsoon gyre shown in Fig. 2. Midget TCs are embedded in the circulation of the gyre in both cases.

Whenever the low-level monsoon circulation of the tropical WNP becomes organized as a gyre, the patterns of the monsoon circulation are characterized by

1) a large (on the order of 2500 km) nearly circular low-level cyclonic vortex;
2) nearly circular isobars with the outermost closed isobar possessing a diameter of roughly 2500 km;
3) a northward displacement of the sea level pressure minimum with respect to the axis of the long-term mean monsoon low-pressure trough;
4) a north–south, low-level high-pressure ridge that separates the sea level pressure depression associated
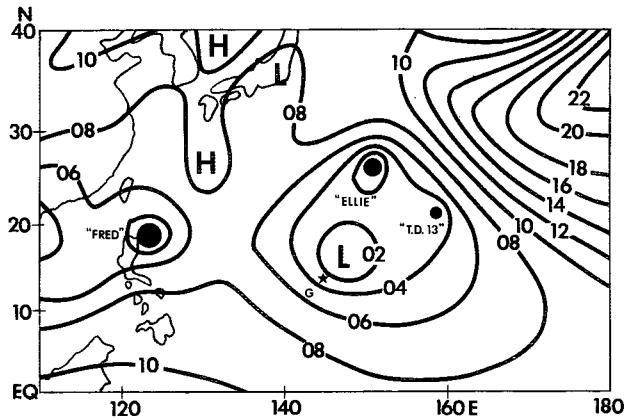

FIG. 2. The August 1991 monsoon gyre. Contours at intervals of 2 hPa show sea level pressure pattern at 0000 UTC 12 August 1991. Black-shaded regions within tropical cyclones Ellie, Fred, and T.D. 13 show where SLP is below 1000 hPa. The location of Guam (13°N, 145°E) is shown by a star (★) labeled, G.

with the gyre from the low-pressure area over the Asian landmass;

5) a persistent band of deep convective cloud rimming the southern through eastern periphery of the circulation;

6) production of a sequence of mesoscale vortices (some of which may become named tropical cyclones) that emerge from the downstream end of the peripheral cloud band; and,

7) a long, two to three week, life span.

Gyres and troughs as distinct patterns of the monsoon circulation encompass a wide range of intermediate possible configurations, and evolution from one pattern to another is possible. Thus, while there is no sharp division between the monsoon circulation as a gyre as opposed to the monsoon circulation as a trough, the concept has some utility as illustrated by the patterns of the circulation in Fig. 1, which are clearly troughs, and by the pattern of the monsoon circulation in Fig. 2, which is unambiguously a gyre. A survey of historical imagery from the Japanese geostationary meteorological satellites—1979 was the first full year of operation—has shown that, at least since then, the phenomenon of the sequential genesis of very small TCs in the WNP has been uniquely associated with monsoon gyres.

Very large intense typhoons (e.g., Super Typhoon Tip in October 1979) often organize the wind field of nearly the entire tropical WNP into one large region-wide cyclonic vortex (JTWC 1979; Merrill 1984). The monsoon gyre as described herein is not the result of the expanding wind circulation of a preexisting TC. The reverse of this sequence of events distinguishes gyres such as the August 1991 monsoon gyre; initially, small TCs are spawned in its peripheral cloud band
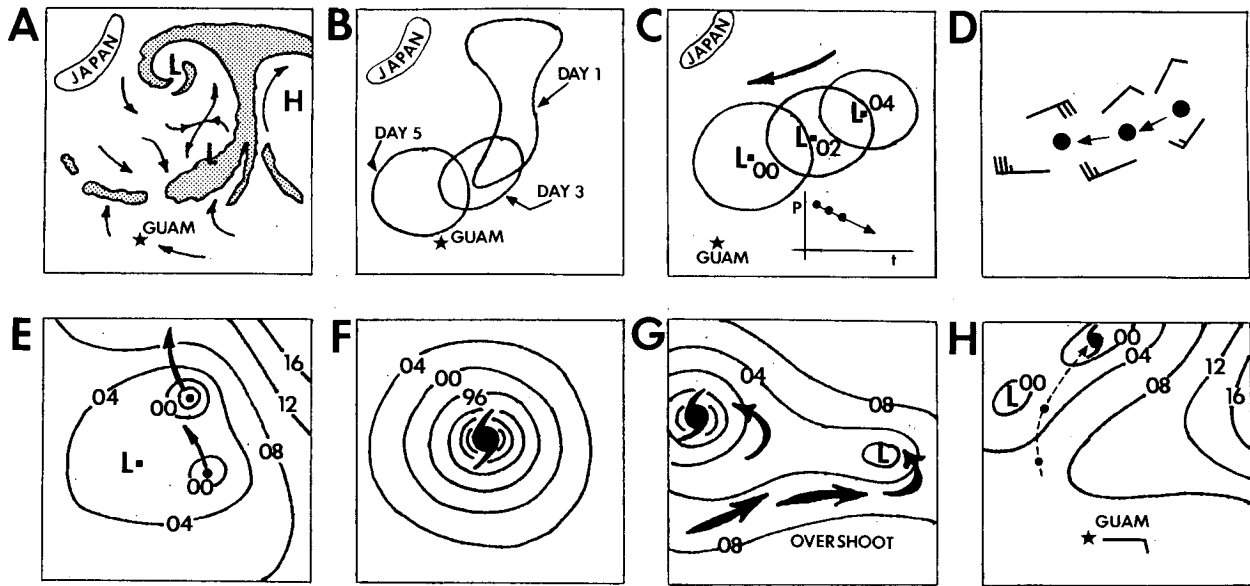
FIG. 3. Schematic diagram illustrating the sequence of important events in the evolution of the August 1991 monsoon gyre: (a) initiation by midlatitude interaction, (b) breakaway of cyclonic circulation in the subtropical latitudes, (c) slow westward migration and gradual sea level pressure drop, (d) gradual acceleration of the peripheral wind field as the gyre migrated westward, (e) formation of small TCs in the southeastern periphery of the gyre, (f) formation of a large TC as the central feature of the gyre, (g) overshoot of southwesterly wind to the east of the original gyre leading to the formation of a new TC that expanded to become a new center of the gyre circulation as the overshot TC decayed, and (h) the eventual lifting of the gyre into midlatitudes as the last TC moved out and the subtropical ridge moved in to occupy the original site of the gyre.

and later, the gyre itself may acquire central convection[5] and become a giant TC.

4. Evolution of wind, pressure, and clouds during the life cycle of the August 1991 monsoon gyre

The general chronological sequence of events observed during the evolution of the August 1991 monsoon gyre are depicted in Fig. 3, and are as follows:

1) in situ development with possible midlatitude forcing;

2) westward migration;

3) steady large-scale lowering of the sea level pressure throughout the region encompassed by the gyre;

4) steady acceleration of peripheral low-level winds;

5) spinup of a sequence of TCs in the southeastern periphery of the gyre;

6) evolution of the gyre itself into a large TC;

7) eastward overshooting of the low-level southwesterly flow; and,

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[5] In operational practice, Dvorak's (1975, 1984) techniques are used to determine the intensity of a tropical cyclone. To classify a tropical disturbance as a tropical cyclone using Dvorak's techniques, deep convective cloud elements must persist for 12 h, or more, within 120 nm of the low-level circulation center.

8) eventual absorption of the gyre into the low-pressure region over Asia.

Each of these events is now described in more detail.

a. In situ development with possible midlatitude forcing

The August 1991 gyre had an intriguing genesis history that suggests a link to, if not a direct forcing by, midlatitude processes. The genesis of the monsoon gyre was preceded by the development of an omega block in the midlatitude flow near the international dateline; indicated in satellite imagery as a large T-shaped cloud pattern. Oriented north–south, this cloud pattern was the visible manifestation of the vertical motion fields in the atmospheric block (Fig. 4). The top segment of the T-shaped cloud pattern is seen to split the subtropical high into two cells. In the upper troposphere, a low zonal-index pattern dominated the mid- and subtropical latitudes, and a cutoff low east of Japan had pushed westerly wind flow (at low levels and aloft) deep into the Tropics north of Guam.

Convection erupting in lower latitudes at the base of the T-shaped cloud band seemed to persist as the midlatitude portion of the T-shaped cloud band decayed and the cutoff low east of Japan filled. The remaining complex of cumulonimbus elements at the base of the T, and its associated weak surface low,
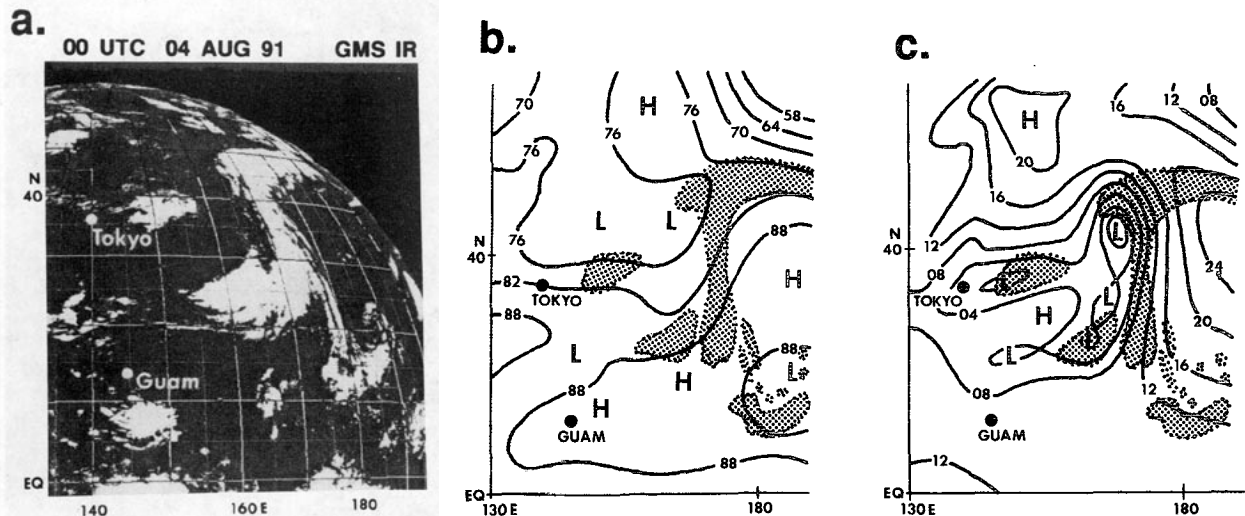
FIG. 4. Synoptic situation at the incipient stages in the formation of the August 1991 monsoon gyre: (a) satellite imagery, (b) 500-hPa chart, and (c) sea level pressure chart for 0000 UTC 4 August 1991. Areas of considerable cold cloud cover are shaded on the 500-hPa and SLP charts. Note: The 500-hPa chart is adapted from the Navy's Fleet Numerical Oceanographic Center (FNOC) analysis; the SLP chart is a subjective analysis by the author.

formed the seed disturbance for the August 1991 monsoon gyre.

b. Westward migration

The persistent complex of cumulonimbus cloud clusters (and the associated weak surface low-pressure area) began a slow west-southwestward migration, tending later to a more westward track (see Figs. 5 and 6). Monsoon southwesterlies, which blew on Guam (13°N; 145°E) for about two weeks during August 1991, backed into Guam from the northeast as the monsoon gyre moved west-southwestward toward Guam; and later, westward passing north of Guam.

c. Large-scale lowering of the sea level pressure

As the gyre migrated westward, its central pressure dropped about one hPa per day for roughly the first half of its 20-day life cycle. Later, as the central region of the gyre began to take on the characteristics of a tropical cyclone (i.e., persistent, centrally located, organized, deep convective cloud), the central pressure began to fall much more rapidly. By 21 August 1991 (over two weeks after the initial establishment of the gyre) the central region of the gyre was occupied by Typhoon (TY) Gladys.

d. Steady acceleration of the peripheral low-level winds

As the central pressure of the gyre steadily fell, the diameter of the outer closed isobar remained relatively constant (Fig. 6). Consistent with this observation was the steady acceleration of the winds blowing around the gyre. Initially, the winds increased in speed partic-

ularly in the cloud band along the southeastern periphery of the gyre, but later, as the central region of the gyre began to evolve into TY Gladys, the whole region of the gyre saw an acceleration of the low-level wind flow to near-gale strength (and higher) within 1000 km of the circulation center.

e. Spinup of a midget typhoon in the gyre's southeastern periphery

During the first half of the life of the gyre, a series of weak tropical depressions (TDs) emerged, one after another, from the major monsoon cloud band into relatively cloud-free air in the northern quadrant of the gyre. These weak TDs were steered in a cyclonic orbit around the center of the gyre. Some of these disturbances remained captured in the flow of the gyre and turned to follow a westward track, while others escaped the influence of the gyre and recurved into midlatitudes. Some of the vortices produced in this manner developed a persistent central convective feature after emerging from the downstream end of the major cloud band and were upgraded to numbered TCs by the JTWC.

f. Organization of the gyre itself into a large tropical cyclone

The first three, of six, significant TCs to be spawned within the gyre's circulation—Tropical Storm (TS) Doug, TY Ellie, TD 13W—formed in the peripheral cloud band of the gyre and were seen to undergo a binary interaction with the center of the gyre (Fig. 7), which at this time was the location of the large-scale pressure minimum in the relatively clear area north and west of the peripheral cloud band (Fig. 8a). Later,
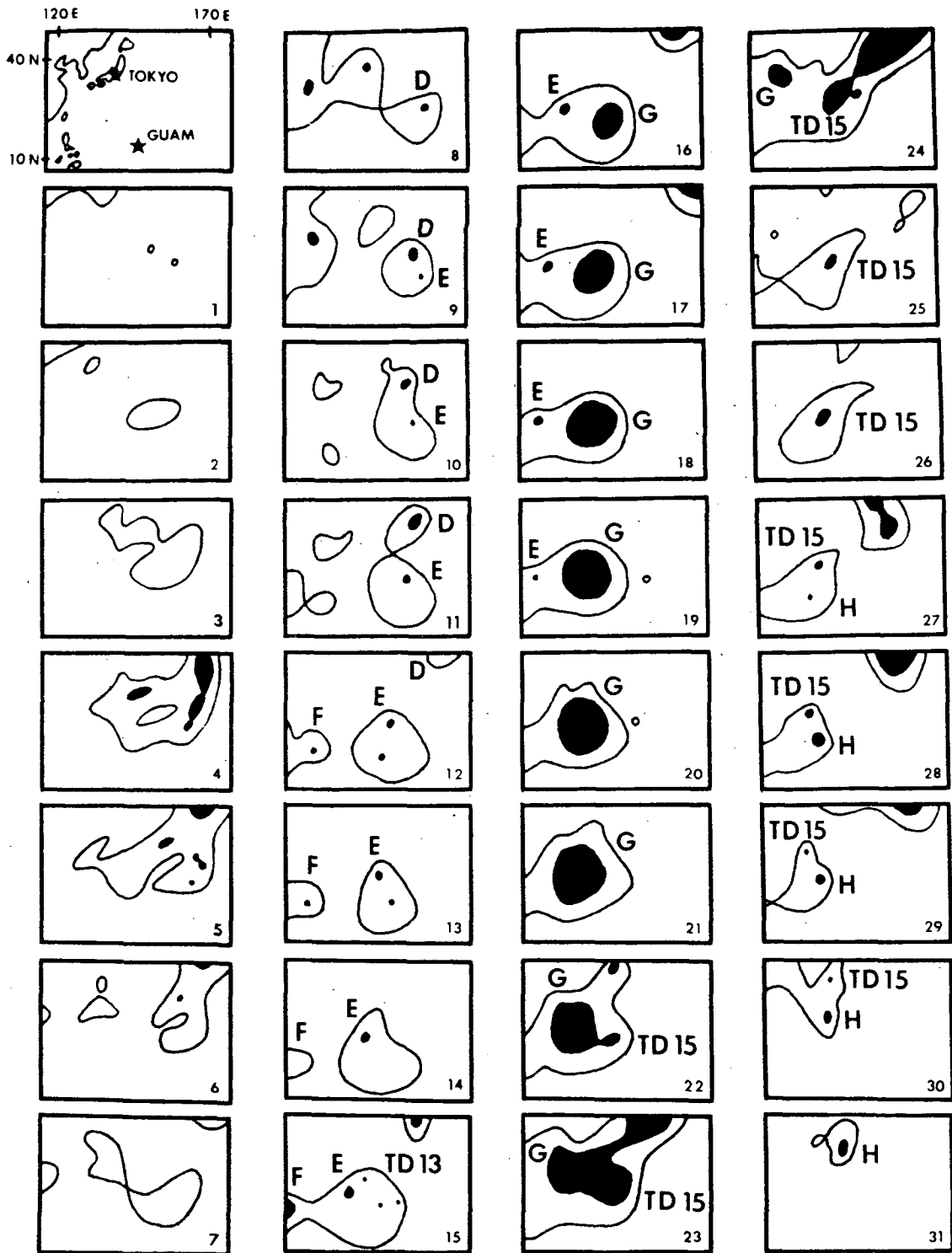
FIG. 5. Western North Pacific sea level pressure for August 1991. Outer contour has a value of 1006 hPa; black-shaded regions are less than 1000 hPa. Panels are at 0000 UTC for the date indicated in the lower right of each panel. Geography key appears in the upper-left panel. Tropical cyclones are indicated: D = Doug, E = Ellie, F = Fred, TD 13 = Tropical Depression 13, G = Gladys, TD 15 = Tropical Depression 15, and H = Harry.
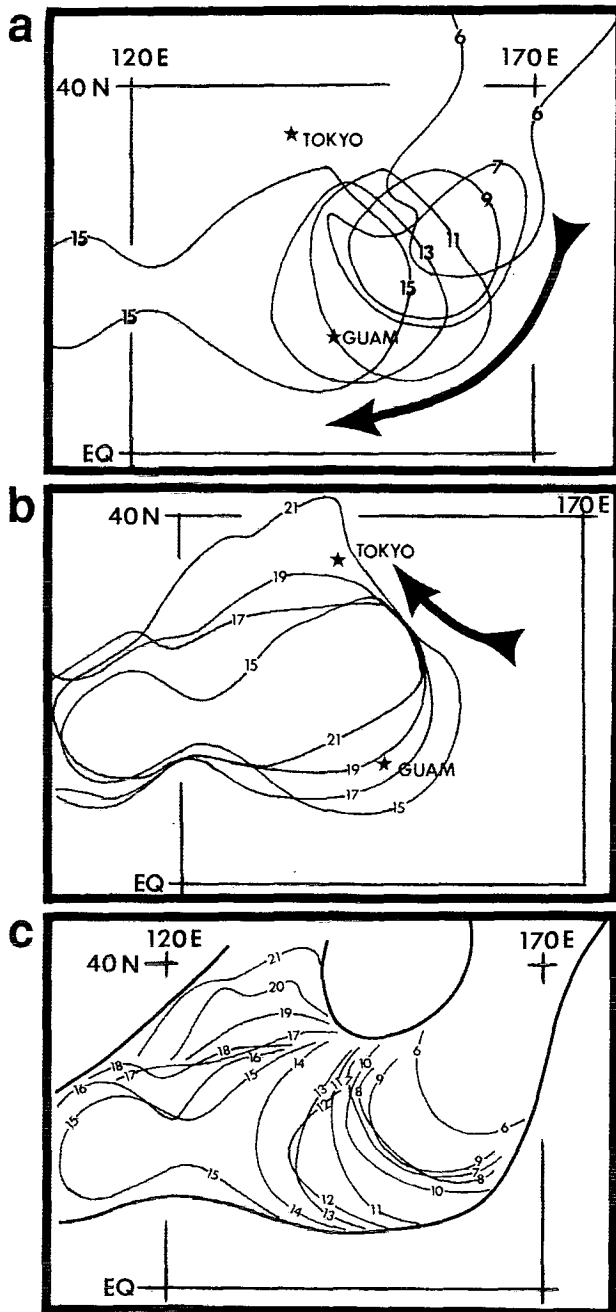
FIG. 6. Time sequence of the westward migration of the monsoon gyre of August 1991. Location of the 1006-hPa contour at 0000 UTC of the indicated day: (a) 6–15 August, (b) 15–21 August, and (c) isochrones of the westward and northwestward advance of the 1006-hPa isobar.

the winds throughout the gyre began to accelerate as the head of the peripheral monsoonal cloud band retracted inward toward the centroid of the gyre. The whole central region of the gyre became more convectively active (Fig. 8b) by virtue of a complex process, discussed more fully in section 5, involving the merger

of the gyre with TS Gladys. The monsoon gyre thereby evolved into a giant TC.

g. Overshooting of the southwesterly low-level flow; eventual lifting of the gyre system into the midlatitudes

As Gladys moved slowly northwestward into the midlatitudes, it was seen to break away from the extensive band of convective clouds in the southwesterly wind flow to its south and southeast. By 19 August, it was apparent that Gladys was becoming detached from the major monsoon cloud band (Fig. 9a), which then extended far to the east of Gladys. By 22 August, Gladys had completely severed from the monsoon cloud band (Fig. 9b). Associated with the overshooting of the monsoon cloud band eastward of Gladys, a low-pressure bulge can be seen protruding from the main circular low-pressure region of the gyre on 22 August (Fig. 5). This bulge later grew in size relative to Gladys and became TD 15W. As Gladys died over South Korea, TD 15W became located near the centroid of the surface low-pressure area of the gyre.

Just as Gladys had severed from the major monsoon cloud band, so too did TD 15W sever from the monsoon cloud band and escape into the midlatitudes leaving behind an intact monsoon gyre (Fig. 5). Tropical Storm Harry (the last of the tropical cyclones to be
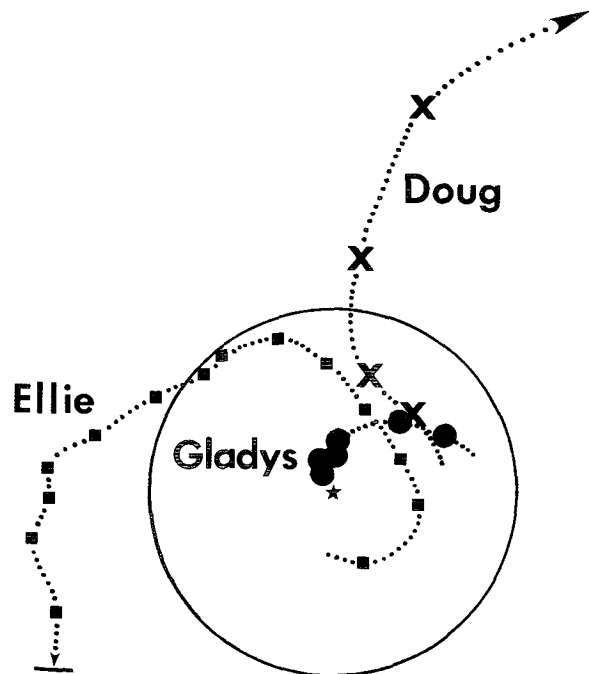

FIG. 7. Movement of Doug, Ellie, and Gladys with respect to the centroid of the 1006-hPa pressure contour of the August 1991 monsoon gyre. Large Xs, small squares, and large dots indicate 24-h time steps for Doug, Ellie, and Gladys, respectively. The background circle has a diameter of about 2200 km and is roughly the size of the observed 1006-hPa isobar.
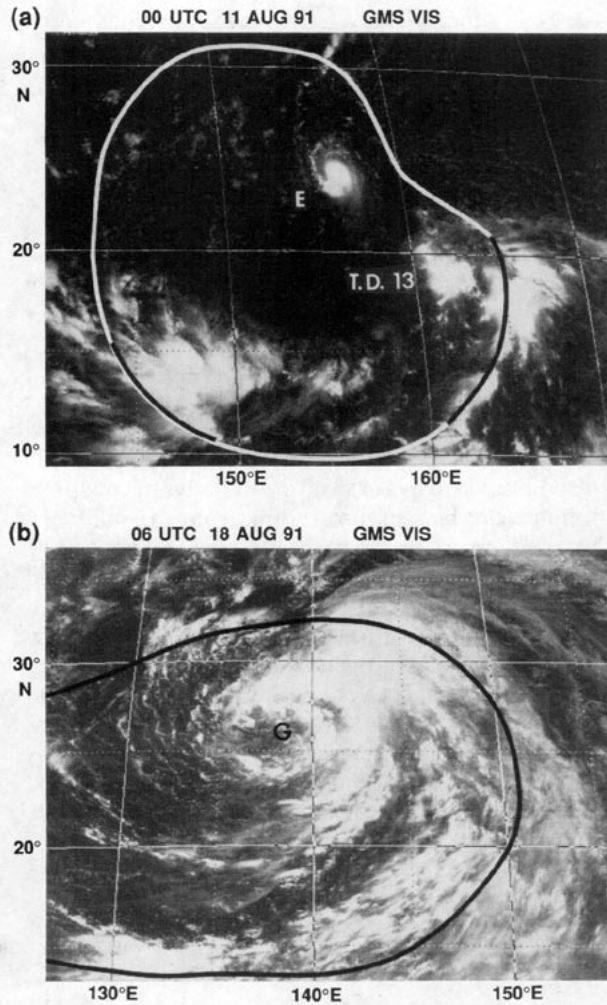
FIG. 8. Visible satellite imagery for (a) 0000 UTC 11 August 1991, and (b) 0600 UTC 18 August 1991. TCs are indicated: E = Ellie, TD 13 = Tropical Depression 13, and G = Gladys. The 1006-hPa contour is shown in each panel by the solid contour.

spawned within the confines of the gyre) pulled (or went with) the low-pressure region out of the Tropics and into midlatitudes upon recurving east of Japan. By the end of August 1991, a low-level ridge of high pressure had moved into the prior location of the gyre (Figs. 5 and 10).

5. TC activity associated with the monsoon gyre of August 1991

Arakawa (1952) noted that midget tropical cyclones that struck Japan were often (if not exclusively) produced within a wide convergence area that formed in the subtropical latitudes (20°–30°N) to the south and east of Japan. During the first half of the life of the August 1991 gyre, a series of small and weak mesoscale vortices were formed, one after another, within the cloud band rimming the southeastern periphery of the

gyre. These weak vortices were steered in a cyclonic orbit around the center of the gyre and emerged from the major monsoon cloud band into relatively cloud-free air in the northern quadrant of the gyre. Some of these disturbances remained captured in the flow of the gyre and turned to follow a westward track, while others escaped the influence of the gyre and recurved into midlatitudes. Some of the vortices produced in this manner developed persistent central convection and were upgraded to numbered tropical cyclones by the JTWC; these include: TS Doug, TY Ellie, and TD 13W.

The August 1991 gyre produced no less than six distinct unnamed mesoscale vortices, which were initially
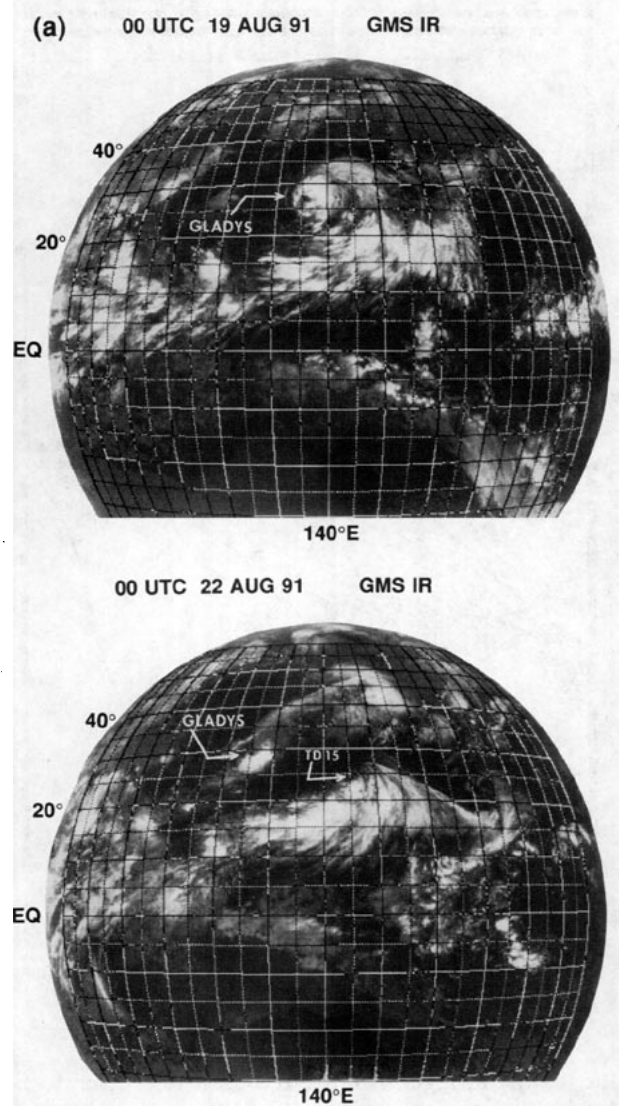

FIG. 9. Full-disc IR imagery from the Japanese geostationary satellite showing: (a) the separation of Gladys from the main monsoon cloud band, and (b) the re-establishment of the monsoon gyre to the southeast of Gladys. Panel (a) is at 0000 UTC 19 August 1991; panel (b) is at 0000 UTC 22 August 1991.
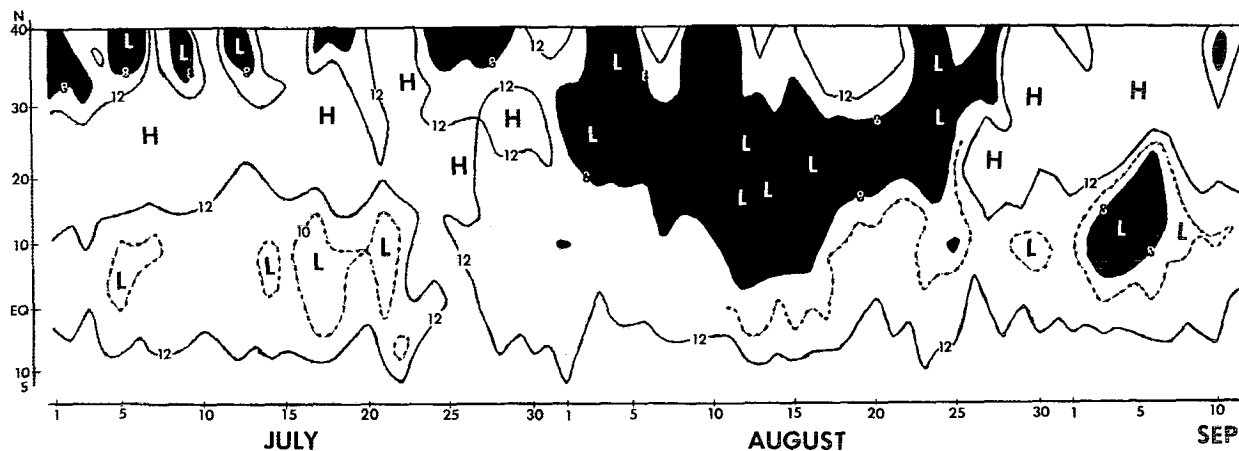
FIG. 10. Time-longitude section of the sea level pressure each day at 0000 UTC along 150°E for the indicated time period. Solid line is the 1012-hPa contour; dashed line is the 1010-hPa contour; the shaded region is below 1008 hPa.

steered around the gyre and then escaped the influence of the gyre and recurved into the midlatitudes. Finally, one of the mesoscale vortices emerged from the cloud band and developed a cloud system center that became TS Doug. Its initial motion was on a cyclonic trajectory in orbit of the center of the gyre, but it managed to escape the influence of the gyre and recurve into midlatitudes (Fig. 7). About a day after Doug was first identified, another small vortex developed in the periphery of the gyre; this small vortex spun up rapidly to become the midget tropical cyclone, Ellie (Fig. 11). Unlike Doug, Ellie resided longer within the circulation of the gyre (Fig. 7), and ended up traveling westward and then west-southwestward into the South China Sea.

FIG. 11. Visible imagery from the Japanese geostationary satellite showing Doug and Ellie at 0500 UTC 9 August 1991.

A day after Ellie had formed, another vortex developed upstream (to the south) from Ellie in the periphery of the monsoon gyre and was upgraded to Tropical Depression (TD) 13W. During the lifetimes of TS Doug, TY Ellie, and TD 13W, the low-pressure center of the gyre was clearly independent of these storms (Fig. 2).

By the time Ellie had dissipated in the South China Sea, the wind speeds throughout the monsoon gyre had increased (see Fig. 12a,b) and the SLP had fallen below 1000 hPa over a large region. As the winds throughout the gyre began to accelerate, a region of deep convective cloud began to wrap inward toward the center of the gyre. By virtue of its persistence and organization, a convective cloud system near the centroid of the gyre was upgraded by the JTWC to TD 14W on 16 August 1991. Shortly thereafter, the deep convection of TD 14W became better organized and moved closer to the centroid of the monsoon gyre (Fig. 7). Tropical Depression 14W was upgraded to TS Gladys on 17 August (Fig. 13a). By 18 August, Gladys's cloud system was being swept around the north side of the centroid of the monsoon gyre (Fig. 13b). By 19 August, a ring of convective cloud elements encircled the centroid of the gyre (Fig. 13c), thus completing the merger of Gladys with the monsoon gyre, and thereby transforming the monsoon gyre into a giant TC.

The transformation of the August 1991 monsoon gyre into a giant TC was complex. Earlier, as in Fig. 2, the TCs in the periphery of the gyre's circulation were clearly separable from an independent low-pressure area near the centroid of the gyre. As Gladys was forming, the downstream end of the peripheral cloud band retracted closer to the centroid of the circulation of the gyre. Perhaps due to increased horizontal shearing of the large-scale low-level wind, Gladys's cloud system was sheared horizontally and, wrapping around the centroid of the gyre, formed a very large ragged eye
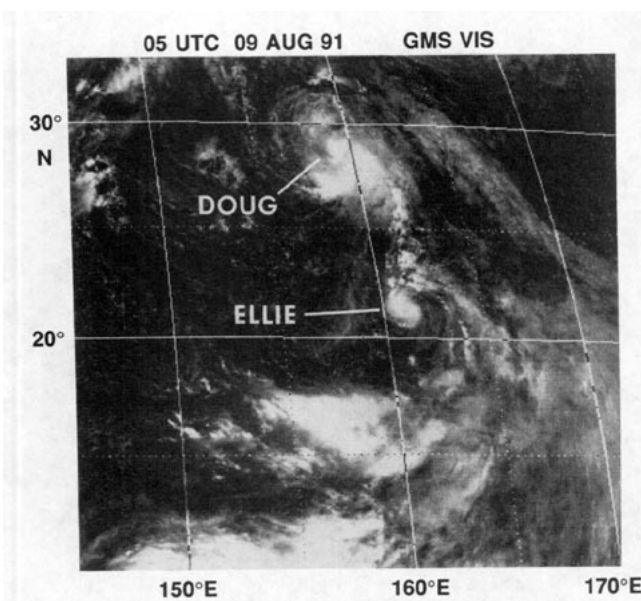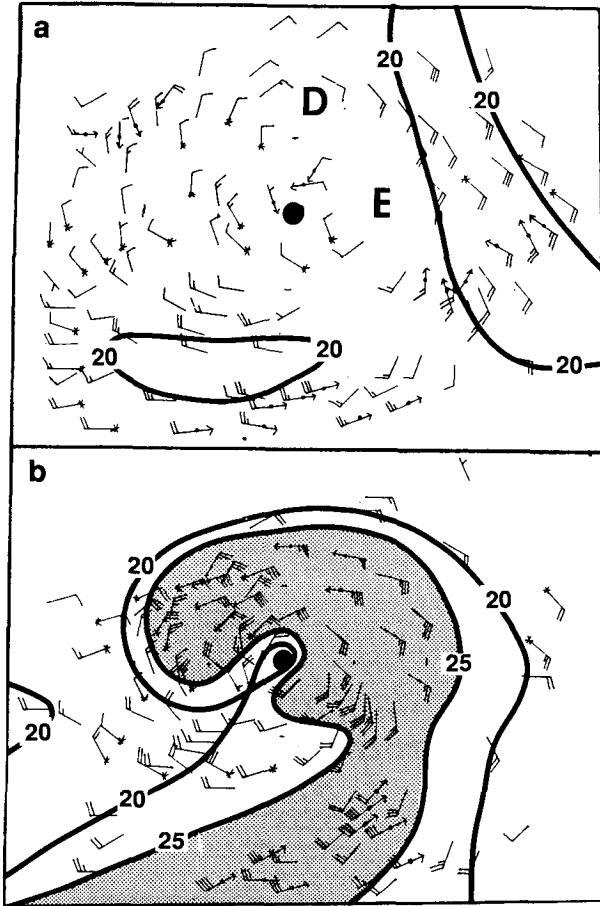
FIG. 12. Illustration of the speed-up of the large-scale low-level wind during the evolution of the monsoon gyre of August 1991. (a) Composite of surface wind reports plotted with respect to the centroid (large dot) of the 1006-hPa isobar from 0000 UTC and 1200 UTC charts from 0000 UTC 9 August to 0000 UTC 12 August. The solid lines are the 20-kt (10 m s^{-1}) isotach. The "D" and the "E" show areas traversed by TCs Doug and Ellie. (b) Same as in (a) except the composite period is 0000 UTC 16 August to 0000 UTC 19 August. Shaded region shows area of wind speed in excess of 25 kt (12.5 m s^{-1}).

(Figs. 13a–c). By virtue of the establishment of persistent central deep convection, the gyre, with its extensive area of surface gales, became a giant-sized TC (retaining the name Gladys) with a size of over one order of magnitude larger than the midget Typhoon Ellie (Fig. 14).

A comparison of the behavior of the small TCs (TS Doug, TY Ellie, and TD 13W) with the behavior of Gladys suggests that two distinct modes of vortex interaction are operating. Ritchie and Holland (1993) used contour dynamics to model the behavior of the interaction of a large and a small vortex in spatial proximity. Depending on the difference of the vorticity between the small and large vortex, very different solutions emerge (Fig. 15). If the vorticity of the small vortex is large with respect to the vorticity of the larger vortex, the smaller vortex survives intact as it orbits
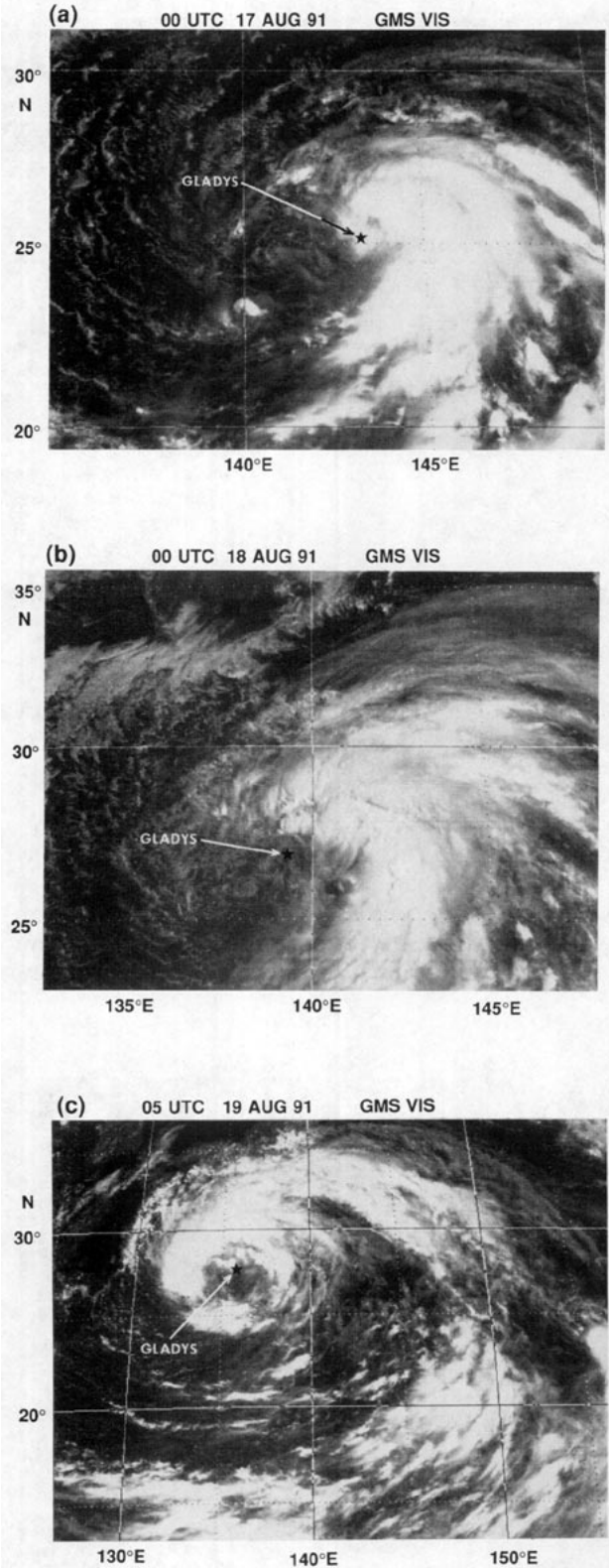

FIG. 13. Visible satellite imagery of Gladys at (a) 0000 UTC 17 August 1991, (b) 0000 UTC 18 August, and (c) 0500 UTC 19 August. Black star indicates the JTWC best-track location of Gladys (JTWC 1991).
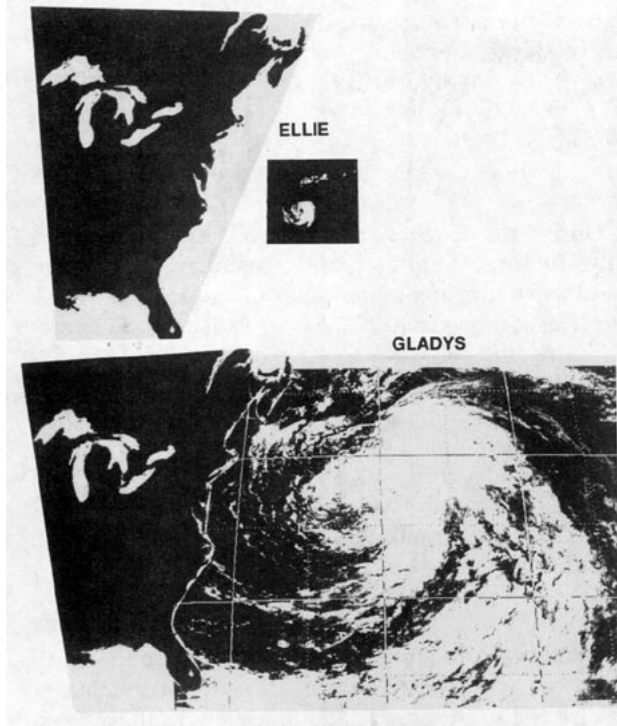
FIG. 14. Schematic illustration of the relative size difference between midget Typhoon Ellie and giant Typhoon Gladys. Both systems are shown to scale as they would appear off the east coast of the United States. A silhouette of the eastern half of the United States appears to the left of each storm; the Great Lakes appear within the dark silhouette of the United States as a geographical reference.

and entrains vorticity from the larger vortex. If the vorticity of the larger vortex is made larger relative to the vorticity of the smaller vortex, a point is reached where the smaller vortex cannot survive the horizontal shearing imposed upon it by the large vortex; it is eliminated as a distinct vortex as its vorticity is stretched into a long filament wrapping around the larger vortex.

It is hypothesized herein, that as long as the vorticity gradient of the gyre is relatively weak, the small TCs that form in the peripheral cloud band can survive the horizontal shear imposed upon them by the larger circulation of the gyre and remain intact. Also, the central convection acquired by the small TCs may also help them resist horizontal shearing deformation. As the circulation of the monsoon gyre intensifies, any small vortex generated in the peripheral cloud band would be rapidly sheared and its vorticity would deform as a long filament and be wrapped into the circulation of the gyre. The behavior of TS Doug, TY Ellie, TD 13W, and TY Gladys with respect to the evolution of the wind field of the monsoon gyre lend observational support to this hypothesis.

6. The monsoon gyre of July 1993

During the latter half of July 1993, the monsoon circulation of the WNP became organized as a mon-

soon gyre similar to the situation in August 1991. The July 1993 monsoon gyre was associated with the formation of three very small TCs (TY Nathan, TS Ofelia, and TY Percy). Fortuitously, ONR and the Naval Postgraduate School were conducting a field experiment called Tropical Cyclone Motion 1993 (TCM-93) [see Harr et al. (1993) for details] during the lifetime of this monsoon gyre. An Air Force Reserve WC-130 instrumented aircraft from the 815th Weather Squadron was deployed to Guam to obtain measurements in and around TCs in the WNP.

Quoting from Harr et al. (1993):

> During the first 12 days of the period [of the TCM-93 field experiment] (20 July–31 July 1993), TY Nathan, TS Ofelia, and TY Percy followed north oriented tracks (Fig. 1a) [not shown] around a low-level monsoon gyre. Each successive tropical cyclone formed west of the
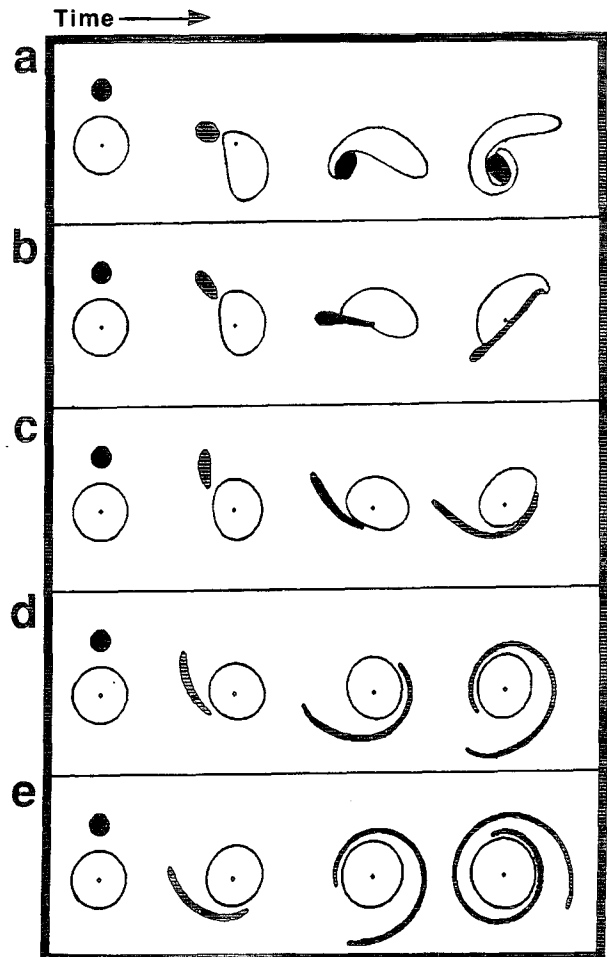

FIG. 15. Interactions of a large and a small vortex (size ratio 3:1) with varying intensity (i.e., vorticity) ratios, small versus large: (a) 3:1, (b) 2:1, (c) 1:1, (d) 1:2, (e) 1:3. The initial separation distance is twice the larger vortex radius in all cases (adapted from Ritchie and Holland 1993).
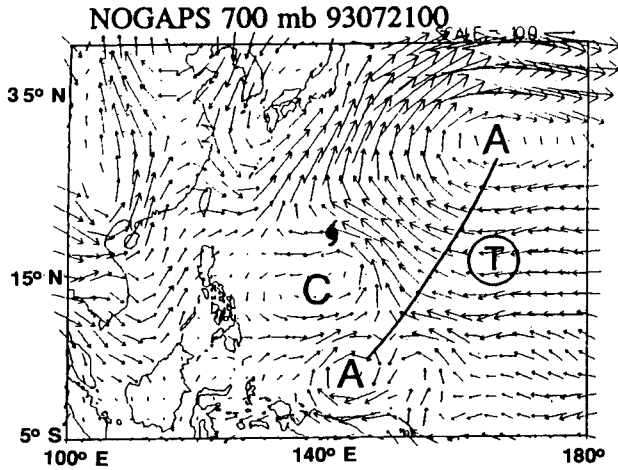
NOGAPS 700 mb 93072100

FIG. 16. The Navy Operational Global Atmospheric Prediction System (NOGAPS) analysis of the 700-hPa winds for 0000 UTC 21 July 1993. The typhoon symbol marks the location of Typhoon Nathan. The position of the 200-hPa TUTT cell is marked by the encircled T. The solid line defines the axis of the subtropical ridge extension. The monsoon gyre is marked by the C. (Adapted from Harr et al. 1993).

preceding storm as the monsoon gyre moved steadily westward.

The character and evolution of the July 1993 monsoon gyre was very similar to that of the August 1991 case. By 0000 UTC 21 July 1993, an independent large-scale cyclonic vortex had formed in the WNP (Fig. 16). As this vortex and its accompanying low-pressure area moved westward over the next 10 days, three very small TCs emerged from the downstream head of the monsoon cloud band and each escaped from the gyre circulation and followed "north-oriented" tracks (JMA 1976) taking them over Japan.

Each of the storms formed westward of the previous storm as the monsoon gyre drifted westward (Figs. 17a–c). By 1 August 1993, the monsoon gyre had merged with the low-pressure area over the Asian landmass. In the WNP, a ridge of high pressure now existed where the gyre had been located several days earlier.

During the course of the westward migration of the July 1993 monsoon gyre, the sequential TC development (each forming to the west of the one prior) in the northeastern quadrant of the gyre was successfully predicted by the TCM-93 forecast team. Three aircraft missions were flown during the period of genesis and intensification of the second storm, TS Ofelia (see Harr et al. 1993).

For the first time since August 1991, a monsoon gyre had formed in the WNP and had produced a sequence of very small TCs. The July 1993 monsoon gyre did not, however, produce a giant TC. The July 1993 monsoon gyre formed about 20 degrees of longitude further to the west of where the August 1991 monsoon gyre had formed, and the winds on the north and western side of the July 1993 monsoon gyre never accelerated to the speeds attained there in the August 1991 monsoon gyre. Perhaps the proximity to the low-pressure over Asia, or the shorter life span of the July 1993 monsoon gyre, prohibited this gyre from becoming as intense (both in circulation and lowered SLP) as the August 1991 monsoon gyre. In many respects, the entire life of the July 1993 monsoon gyre was analogous to the first half of the life span of the August 1991 monsoon gyre when that gyre (August 1991) was producing very small TCs in its northeastern quadrant. The TCM-93 dataset may provide a means to examine the mechanisms leading to the formation of very small TCs in the peripheral cloud band of a monsoon gyre.
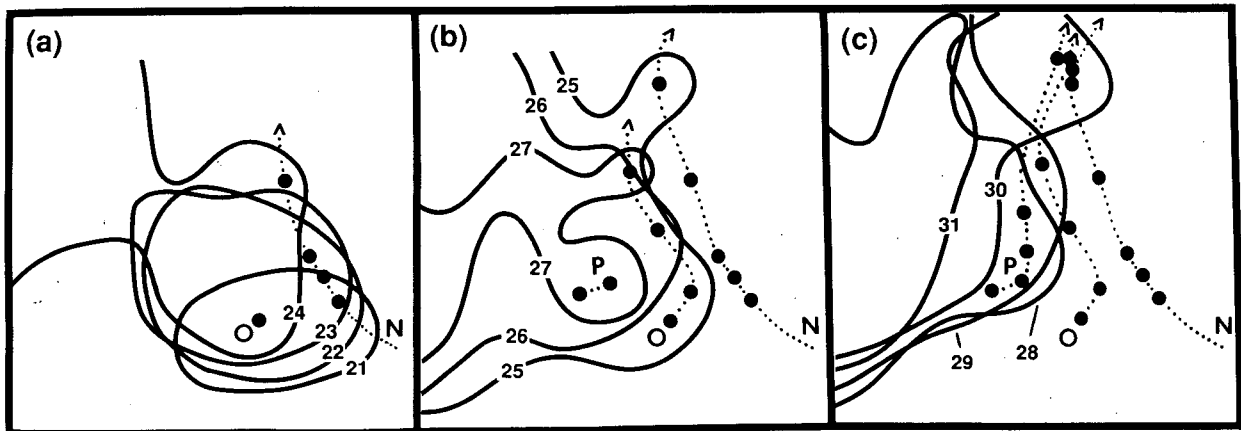

FIG. 17. Illustration of the west-northwestward movement of the monsoon gyre of July 1993. (a) The 1008-, 1008-, 1006-, and 1004-hPa contour of SLP at 0600 UTC 21, 22, 23, and 24 July, respectively. (b) The 1006-hPa contour of SLP at 0600 UTC 25, 26, and 27 July. (c) The 1006-hPa contour of SLP at 0600 UTC 28, 29, 30, and 31 July. Dots show 6 UTC position of TCs Nathan (N), Ofelia (O), and Percy (P), which acrue on each subsequent panel.

7. Summary and conclusions

The low-level summer monsoon circulation of the tropical western North Pacific can appear in the form of a trough or a large gyre. These two broad categories of the monsoon circulation have important implications for the site of genesis, size, and subsequent motion of TCs that form in them.

This paper focused upon the flow pattern of a monsoon gyre that formed during August 1991. This monsoon gyre had a long (20-day) life and was associated with the genesis of six TCs. Two modes of tropical cyclogenesis appeared to be acting: the first mode resulted in a series of very small tropical cyclones forming in the southeastern quadrant of the gyre; the second mode featured the formation of a very large TC near the center of the gyre. It is hypothesized that the difference between the relative magnitude of the vorticity of the gyre (which was increasing with time) and the vorticity of the mesoscale vortices that formed in the monsoon cloud band in the periphery of the gyre was a determining factor in the manner in which the TCs and the gyre interacted. When the vorticity of the gyre became too high, any small vortices generated in its peripheral cloud band would have been rapidly deformed by the horizontal shearing flow of the larger circulation.

The August 1991 monsoon gyre was representative of a distinct pattern type of the monsoon circulation of the WNP, which repeats roughly once every other typhoon season at some time during July, August, or September. Recognition of the gyre pattern in real time can allow for a relatively accurate 2–3 week outlook of the character of the TC activity to be expected in the WNP: as the gyre drifts westward, a series of small TCs (each forming westward of the prior cyclone) emerges from the downstream end of the monsoon cloud band associated with the gyre. An accurate prediction of a sequence of small TCs in the WNP was realized during the observing period of the TCM-93 mini–field experiment (Harr et al. 1993) when a monsoon gyre formed and dominated the circulation during the last two weeks of July 1993.

The monsoon gyre is associated with TCs of extremely small and extremely large size. Only a few studies have been written that have focused on TC size (e.g., Arakawa 1952; Brand 1972; Merrill 1984). Further understanding of the mechanisms governing TC size may well arise from a close study of the monsoon gyre. Given the relative rarity of the formation of monsoon gyres with a structure resembling that of the monsoon gyre of August 1991, it would appear that some special conditions in the general circulation of the Asian Tropics must be met in order for the monsoon circulation of the WNP to become organized as such. It is hoped that future theoretical and modeling studies will provide insight for a precise physical explanation.

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