Environmental Conditions Prior to Formation of a Midget Tropical Cyclone during TCM-93

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ABSTRACT

During a 10-day period in the Tropical Cyclone Motion (TCM-93) field experiment over the tropical western North Pacific, tropical cyclone formation occurred in association with persistent deep convection that was observed over low-level, north-oriented confluent flow between a large monsoon gyre to the west of a strong subtropical ridge. The convection was also modulated by a strong diurnal cycle with a convective maximum just before dawn and a convective minimum during the late afternoon. Observations from two aircraft observing periods (AOPs) during two consecutive daytime periods identified three distinct mesoscale convective vortices (MCVs) in the persistent deep convection. During the initial AOP (AOP-1A), a well-defined mesoscale circulation at 500 mb was located directly above the strong low-level, south-southwesterly confluent flow. However, reduction in convection and associated midlevel forcing during the convective minimum period contributed to the decay of the MCV before it could penetrate downward through the strong low-level flow to tap ocean surface energy sources. During the second AOP (AOP-1B), which was approximately 24 h after AOP-1A, two MCVs were identified by aircraft observations. A northern MCV, which dissipated shortly after the AOP, had a structure similar to the observed MCV in AOP-1A and was also located directly above the strong low-level north-oriented flow. A second midtropospheric MCV over the southern portion of the aircraft operating area extended down to 850 mb and was located in the cyclonic shear of the low-level flow. Although convection over the large area was decreasing during the diurnal minimum, several convective cells formed and grew in association with local low-level convergence between the low-level MCV circulation and the large-scale flow. In contrast to AOP-1A, this convection persisted and acquired a rotation as part of a northward-moving circulation that can be traced to a small low-level mesoscale circulation in satellite visible imagery approximately 10 h after the AOP as the same circulation observed over the southern region of AOP-1B. Satellite visible imagery documents the explosive convective development associated with the lower-level circulation that led to the formation of Tropical Storm Ofelia. It is concluded that the southern MCV in AOP-1B was able to persist because of its extension to low levels, which was linked to its location on the cyclonic shear side of the strong low-level flow.

1. Introduction

The primary objective of the Tropical Cyclone Motion (TCM-93) field experiment was to collect in situ observations of mesoscale convective systems (MCSs) that may interact with tropical cyclones to cause track deflections. A secondary hypothesis of TCM-93 addressed the role of tropical MCSs in the development of tropical cyclones. Relationships between mesoscale convectively generated vortices (MCVs) that have been identified in some MCSs (Bartels and Maddox 1991) and tropical cyclone formation have been proposed by Bosart and Sanders (1981) and Fritsch et al. (1994) based on case studies, and by Chen and Frank (1993) with supporting numerical simulations. Each study has emphasized the necessity for the MCS to be long-lived. Also, a key point is how a cold mesohigh that is typically found beneath a large MCS becomes transformed to a warm cyclonic circulation. Over a warm tropical ocean, this transformation may be related to downward penetration of a midtropospheric MCV toward the surface. In one proposed scenario (Emanuel 1986; Fritsch et al. 1994), the low-level winds might produce a critical level of energy transfer from the ocean to the atmosphere.

In this paper, TCM-93 observations from two aircraft observing periods (AOPs) are analyzed to describe the environmental conditions, which included several well-developed MCVs, prior to the formation of a midget tropical cyclone. During the initial 10 days of the TCM-93 field program, the large-scale, low-level circulation over the tropical western North Pacific contained a large monsoon gyre over the Philippine Sea and a strong subtropical ridge to the east. Strong north-oriented confluent flow between these circulations was related to the northward movement of Typhoon (TY) Nathan and a south-to-north-oriented region of persistent deep convection. The deep convection was mod...
ulated by a strong diurnal cycle with convective maximum periods occurring between 1800 and 2000 UTC (0400–0600 local time) and convective minimum times between 0600 and 0800 UTC (1600–1800 local time), which correspond with times of peak diurnal variability in deep convective activity observed by Chen and Houze (1996, manuscript submitted to Quart. J. Roy. Meteor. Soc.) over the tropical Pacific warm pool. The strong diurnal cycle in oceanic deep convection has often been identified with cloud–radiation interactions (Gray and Jacobson 1977; McBride and Gray 1980; Randall et al. 1991). In this context, the observed cycle during the TCM-93 period may have been forced by increased convergence into the low-level confluence zone by radiation-induced subsidence from less cloudy areas to the west (monsoon gyre) and east (subtropical ridge) of the confluence zone. An alternate explanation by Chen and Houze (1996, manuscript submitted to Quart. J. Roy. Meteor. Soc.) is that the diurnal heating of the ocean surface and atmospheric boundary layer may explain the growth of convective cells during late afternoon, which continue to grow throughout the following nighttime period. The first AOP (AOP-1A), which was centered at 0600 UTC 23 July, documented the structure of a midlevel MCV during the daylight hours following an overnight period of deep convection in the north-oriented confluent flow between the monsoon gyre and subtropical ridge. Satellite imagery and aircraft data from a second AOP (AOP-1B) centered at 0800 UTC 24 July clearly identified two distinct MCVs in the confluent region. Important differences were noted in the vertical extent of the two MCVs and in their locations in relation to the north-oriented confluent flow. During the nighttime hours following AOP-1B, the northward movement of both MCVs was evident in infrared satellite imagery. By the following morning, the northern MCV had dissipated, but upper-level shear had displaced the cirrus shield over the southern MCV and a low-level mesoscale circulation was clearly defined in visible satellite imagery. Although no AOP was possible on this day (i.e., 25 July), hourly visible Geostationary Meteorological Satellite (GMS) images documented the initiation of vigorous deep convection over the low-level circulation during a 6-h period that culminated in the formation of a midget tropical cyclone [Tropical Storm (TS) Ofelia]. Intensification to a tropical storm was verified on the following day (26 July) when flight-level winds exceeding 50 kt (25 m s⁻¹) were measured during a third AOP (AOP-2A).

Little is known about the genesis of midget tropical cyclones. Arakawa (1952) describes the origin of the midget typhoons that strike Japan as being a “convergence area in the subtropics.” Brand (1972) observed that midget tropical cyclones in the western North Pacific tended to occur in a corridor near the east Asian coast. M. Lander and C. Guard (1995, personal communication) have documented several cases of midget tropical cyclones that formed in association with monsoon gyres, which are long-lasting, quasi-circular circulations that may be as large as 2000 km in diameter (Lander 1994). One of the characteristics of these monsoon gyre-related tropical cyclones is a tendency for recurring formations. For example, the midget TY Ellie (1991) is one of six tropical cyclones that formed in the same monsoon gyre over a three-week period (ATCR 1991, p. 91). In addition to Ellie, TS Doug, Tropical Depression (TD) 13W, TD 15W, and TS Harry were all small tropical cyclones that formed from this gyre. Monsoon gyre-related tropical cyclones, which may also have unusual tracks (Carr and Elsberry 1995), tend to have a midseason (July–August) maximum, which is also the period of maximum midget tropical cyclone occurrence found by Brand (1972) and Merrill (1984).

Understanding the favorable (and limiting) environmental conditions for midget tropical cyclone formation is necessary for a comprehensive theory of tropical cyclogenesis. The focus of this study is the role of MCS (s) and associated MCV (s) in the formation of a small tropical cyclone. In this case, it is hypothesized that large-scale circulations defined an environment favorable for development of persistent deep convection with associated MCV formation, and one MCV defined the preexisting disturbance from which the midget TS Ofelia formed. The specific data types and methods of analyses are described in section 2. The characteristics of the large-scale circulation over the tropical and subtropical western North Pacific that are contributing to a large region of persistent deep convection are defined in section 3. In section 4, observations from AOP-1A are used to indicate that MCV formation is occurring within the region of persistent deep convection 48 h prior to the formation of the TS Ofelia. Data from AOP-1B are used in section 5 to document the continued presence of MCVs in the same region. In section 6, the combination of the aircraft observations with hourly GMS imagery during and following AOP-1B identify one MCV that was observed during AOP-1B as the preexisting disturbance for the small TS Ofelia. Conclusions and discussion of the role of MCSs and associated MCVs in tropical cyclone formation are presented in section 7.

2. Data and analysis procedures

The small TCM-93 field experiment was conducted in the western North Pacific from 20 July 1993 to 12 August 1993. The primary data platform was a WC-130 instrumented aircraft from the Air Force Reserve 53d Weather Squadron. Seven aircraft missions were conducted in which flight-level and Omega dropwindsonde (ODW) data were collected (Harr et al. 1993). The two AOPs of interest in this study were conducted from 0311 UTC to 0934 UTC 23 July 1993 (AOP-1A) and 0206 UTC to 1204 UTC 24 July 1993 (AOP-1B).

Results of this study are based on direct examination of relevant aircraft, station, and satellite data.
analyses are constructed from the observations to allow for computation of derived quantities that aid in the examination of the environmental conditions prior to the formation of TS Ofelia.

a. Observations

Aircraft operations were generally designed to provide a 100-km spacing between ODW observations. The processing of ODW soundings was patterned after Franklin (1987). Pressure, temperature, and relative humidity measurements transmitted from the ODW were collected on the aircraft at 10-s intervals, and wind speed and direction were computed at 30-s intervals from Omega navigational signals. The raw ODW data were manually examined to identify basic problems that may have been caused by calibration errors, moisture contamination of the sonde sensors, and adjustment of the sensors to ambient conditions after launch from the aircraft (Franklin 1987). The 10-s data were filtered with a 100-mb low-pass digital filter and sampled at 50-mb intervals between flight level and 950 mb. Low-pass-filtered winds were also interpolated at the 50-mb intervals. Final checks on the data included the examination of the vertical consistency of the individual profiles and the horizontal consistency of each variable between adjacent observations. Manual observations taken by the Aerial Reconnaissance Weather Officer onboard the aircraft at each ODW launch were used at the uppermost observation in each ODW sounding.

Flight-level observations at 10-s intervals were filtered with a 15 min low-pass digital filter and sampled at 7.5-min intervals, which is approximately every 50 km. The aircraft data were also coordinated with hourly satellite imagery that is used to define the convective signatures of the large-scale circulation and individual MCSs.

Additional data, which include real-time synoptic data and rawinsonde observations from island stations, were obtained from the Automated Weather Network at the Joint Typhoon Warning Center (JTWC) on Guam. Analyzed fields of heights, winds, temperature, and moisture were also obtained from the Fleet Numerical Meteorology and Oceanography Center (FNMC). All observations are positioned in a reference frame that is centered at 0600 UTC 23 July 1993 for AOP-1A and 0800 UTC 24 July 1993 for AOP-1B.

b. Gridded analysis procedures

The analysis of ODW and flight-level data is augmented by the use of gridded fields of wind, height, temperature, and vapor pressure that are constructed with a two-dimensional multiquadric interpolation technique (Nuss and Titley 1994). The multiquadric interpolation method uses radial basis functions that are circular hyperboloids, which differs from statistical interpolation techniques that use covariance functions between the data field at observation points and other points as basis functions. The multiquadric technique was found by Nuss and Titley (1994) to provide analyses that closely fit the observations at an accuracy that is equal or greater than both the Barnes (1973) and Cressman (1959) successive correction techniques. Franke (1985) found the multiquadric technique to be as accurate as statistical interpolation methods.

The analysis is constructed on a 1° latitude–longitude grid, which is consistent with the 100-km average spacing between dropwindsonde locations. For the purpose of this study, the horizontal analysis domain is taken to be between 13°–19°N and 138°–145°E, while the vertical domain proceeds in 50-mb increments between 950 and 400 mb, which is the highest flight level. In addition to the ODW and flight-level data, mandatory and significant level rawinsonde data from Guam (13.5°N, 144.9°E) are interpolated to 50-mb intervals and then used in the analysis procedure. Details of the multiquadric procedure, which include the coupling of heights and winds and application of a observation weighing factor, are described in general by Nuss and Titley (1994) and in reference to analysis of TCM-93 observations by Harr and Elsberry (1996).

The multiquadric analyses are obviously limited by the distribution of data. Within the regions that were densely sampled by aircraft observations, the multiquadric analyses closely fit the observations. Although there would be serious analysis quality concerns away from the dense set of aircraft observations, all conclusions based on these fields are derived from the analyses defined within the dense aircraft observation region.

3. Large-scale circulation

Over the period from 19 July to 27 July 1993, repeated tropical cyclogenesis (TY Nathan, TS Ofelia, and TY Percy) occurred along the eastern edge of the monsoon gyre circulation (Harr et al. 1993). In addition to each formation being similar, each tropical cyclone followed a similar north-oriented track toward landfall over southern Japan (Fig. 1). During this period, the low-level large-scale circulation over the western North Pacific contained a large cyclonic gyre at 22°N, 139°E (Fig. 2b). As defined in Lander (1994), large cyclonic gyres have been observed to have diameters on the order of 2000 km and a life span of a week or more. Low-level circulations were such that persistent deep convection was continually being forced in a region of confluence between the gyre to the west and the subtropical ridge to the east (Fig. 2b). At 200 mb, subsidence under an intense cell within the tropical upper-tropospheric trough (TUTT) at 19°N, 160°E (Fig. 2a) contributed to the strengthening and westward extension of the lower-level subtropical ridge (Fig. 2b).

As TY Nathan moved northward between the gyre and the subtropical ridge, the anticyclone began to
4. Aircraft observing period AOP-1A

The mission plan for AOP-1A was designed relative to a fix of persistent deep convection that was based on GMS enhanced IR and visible satellite imagery. The primary focus of the mission was to determine the structure of a MCS that was located in a region where two successive diurnal convection cycles had occurred. Prior to takeoff, a circular area of reduced convection became visible in satellite imagery (Fig. 3) after upper-level winds had displaced the cirrus shield to the southwest. Based on the satellite signature, aircraft flight operations at 500 mb and 400 mb were centered at 16°N, 141.5°E, which was near the center of the area of reduced convection.

Flight-level and dropwindsonde winds at 500 mb (Fig. 4a) clearly reveal the existence of a midtropospheric mesoscale cyclonic circulation that presumably formed under a stratiform rain area as in many previous tropical (Zipser 1977; Houze 1977) and midlatitude (Smull and Houze 1985; Raymond and Jiang 1990; Hertenstein and Schubert 1991) MCS studies. Although the data coverage was not as complete as at 500 mb, the mesoscale circulation is also evident in aircraft observations at 400 mb (not shown). At 700 mb (Fig. 4b), dropwindsonde observations along 16°N and west of 141°E suggest a very weak downward extension of the midlevel circulation, which is also tilted to the west. The wind profile from ODW 3 at 16°N, 141.5°E (Fig. 5), which was located immediately west of the 500-mb center, suggests that the vortex structure is gradually weakening between 500 and 700 mb. Further, the downward extension of the well-defined 500-mb circulation is evidently prevented by the presence of the low-level southwesterly flow that is below the 500-mb circulation center. At 850 mb (Fig. 4c), the entire set of aircraft winds indicate southwesterly flow around the large monsoon gyre (Fig. 2b).

The inference of the MCV forming under a stratiform rain area is based on several ODW soundings (e.g., Fig. 5) that have the familiar onion-shaped profile (Zipser 1977) with a layer of warm, dry air below a nearly saturated upper-tropospheric layer and above a saturated lower-tropospheric layer. Although the strong low-level southwesterly flow (Fig. 4c) around the monsoon gyre below the 500-mb circulation and the presence of low-level clouds (Fig. 3) are consistent with warm, moist conditions at low levels, ODW soundings such as Fig. 5 often indicate a totally saturated environment at the very lowest levels, which is probably erroneous due to sensor wetting after passage through low-level clouds or precipitation (Franklin 1987). However, the detailed sounding structure that is evident above the low-level saturated levels indicates reliable data, which are used to infer the atmospheric structure throughout the majority of the ODW descent.

Vortex stretching between mesoscale ascent in the stratiform rain area and mesoscale downdrafts induced below the stratiform layer is generally considered to be

![Diagram](image-url)
the mechanism for the generation of the midtropospheric vortex (see explanation in Houze 1993). An east–west cross section of divergence and associated kinematic vertical motion estimate calculated from the multiquadric analysis along 16°N, which is directly along the aircraft flight path (Fig. 4a), is shown in Fig. 6. A midlevel convergence maximum with upward motion above and downward motion below is centered near 141.5°E, which is almost coincident with the 500-mb circulation center (Fig. 4a). Downward motion is evident only to 700 mb, below which the strong low-level southwesterly flow is dominant.

Values of potential vorticity (PV), which are calculated on isobaric surfaces as specified in Hoskins et al. (1985), define a midlevel maximum along 16°N at 141.5°E (Fig. 7). At 16°N, the diameter of the midlevel vortex in the east–west direction is approximately 400 km. The center has a weak downward extension to 700 mb that is tilted toward the west. The downward extension of the midlevel circulation appears to be par-
tially blocked by the undercutting of minimum PV associated with the anticyclonic shear of the low-level confluent flow (Fig. 4c). These PV values based on the AOP-1A flight-level and ODW wind and temperature observations document a well-defined MCV that existed in the area of persistent deep convection.

Throughout the AOP, convective activity over the aircraft operations region steadily decreased as expected during the minimum in the diurnal cycle of deep convection over oceanic regions. When convection again increased over the region following the AOP, no distinct satellite feature could be uniquely identified with the observed MCV. It is hypothesized that during the convective minimum a reduction in the conditions that would be favorable for MCV generation and maintenance made it unlikely that the midlevel MCV would penetrate through the strong low-level southwesterly flow associated with the large-scale circulation. That is, this mesoscale system could not tap into ocean heat and moisture sources via surface fluxes, and therefore this MCV dissipated.

The maintenance of the MCV could also be examined with respect to the mechanisms defined by Fritsch et al. (1994). In their hypothesis, an MCV may be maintained by low-level air that overtops the mesoscale circulation and is lifted up isentropic surfaces associated with the cold air underneath the MCV to generate new convection near the MCV center. For the AOP-1A case, a north–south cross section of winds and divergence along 141.5°E (Fig. 8) indicates that the low-level southwesterly flow was certainly strong enough to overtake the midlevel MCV (Fig. 4c). However, the flow approaching from south of the MCV, which is centered at 16°N, is subsiding so that the southwesterly flow is not being lifted as in the Fritsch et al. (1994) case. Soundings in the southwesterly flow upstream from the MCV (Fig. 9) indicate a very warm dry layer below 800 mb that is separated from a very shallow saturated layer by a strong inversion near 975 mb. In this case, the strong north-northeasterly upper-level winds that are evident in the cirrus streaks that (Fig. 3) are responsible for pushing the upper-level clouds to the southwest of the MCV such that the low-level air upstream of the MCV is flowing through unsaturated downdrafts and not being lifted to maintain convection in the MCV.

Although the structure of the MCV was adequately sampled during the AOP, it is not possible to determine conclusively how long the MCV had persisted. Two possibilities are (i) that the MCV formed during the most recent period of deep convection that occurred approximately 12 h prior to the AOP-1A center time, or (ii) that the MCV formed during an earlier period of maximum convective activity and had persisted through at least one convective minimum time. Because the circular region of reduced cloudiness in the satellite image of Fig. 3 was the first indication in many
days of the possible existence of a MCV, and because of the continued presence of the strong low-level southwesterly flow, it seems unlikely that the observed MCV would have been able to persist through one or more periods of reduced convective activity when conditions throughout the midtroposphere would not be conducive to MCV generation. Consequently, scenario (i) above would seem to be a more likely sequence. A second AOP (AOP-1B) would investigate conditions following the new period of deep convection.

5. Aircraft observing period AOP-1B

Satellite imagery and rawinsondes from island stations indicated that the entire system of TUTT cell, subtropical ridge, and monsoon gyre moved westward between the end of AOP-1A (1000 UTC 23 July) and the beginning of AOP-1B (0400 UTC 24 July). As in AOP-1A, the deep convection began to dissipate during the morning hours of 24 July, and the main cirrus shield retreated to the southwest due to combined upper-level winds from the outflow of TY Nathan to the north and the TUTT cell to the east.

Prior to the start of AOP-1B, a small cyclonically rotating circulation was evident in visible satellite imagery (labeled A in Fig. 10) near 17°N, 141.5°E, which is 1° latitude north of the location of the circulation observed during AOP-1A. To define the low-level structure of this circulation, the AOP-1B flight plan was designed to proceed east to west along 17°N at 850 mb, then climb to 700 mb and proceed west to east at the same latitude. The aircraft would then complete several alpha patterns, which would be centered near 17°N, 141.5°E at 700 and 500 mb levels. However, rapid movement of the small circulation to the north, which was evident from the movement of the convective signature (labeled A in Fig.

Fig. 4. Flight-level (small wind) and dropwindsonde (large wind) winds and streamlines at (a) 500 mb, (b) 700 mb, and (c) 850 mb during AOP-1A. Streamlines are derived from the multiquadric analyzed winds. A long wind barb equals 5 m s⁻¹ (10 kt), and a short wind barb equals 2.5 m s⁻¹ (5 kt).
Fig. 5. Skew T–lnp temperature (right) and dewpoint temperature (left) and winds (long barb is 5 m s⁻¹) for ODW 3 (16°N, 141.5°E), which was deployed at 0354 UTC 23 July 1993.

1B was very identifiable, the circulation could be tracked until it dissipated nearly 12 h later (see Fig. 19).

Winds along the 700- and 850-mb flight legs at 17°N reveal a low-level circulation to the west of 140°E (Figs. 12b,c). This circulation may have been associated with a large MCS near 17°N, 140°E (labeled B in Fig. 10) that was beginning to dissipate at the beginning of the AOP. Although the aircraft sampled only the northern and eastern portions of this circulation, it is apparently more broad than both the circulation to the north and the circulation identified during AOP-1A. Another distinct difference is the strong circulation at 700 mb (Fig. 12b), which extends down to 850 mb (Fig. 12c). In addition, this circulation is clearly on the cyclonic shear side of the strong low-level southerlies that are located between 140° and 141°E (Figs. 12b,c). Although deep convection over the region had generally weakened during the AOP, new cells were growing to the south of the circulation along 15°N and between 137° and 139°E (labeled B in Fig. 11). These growing cells may be associated with enhanced local low-level confluence between the large-scale southwesterlies and the flow around the mesoscale circulation.

The temperature and dewpoint profiles (Fig. 13) from ODW 1 (17°N, 138.4°E) indicate a warm, dry layer between 875 and 725 mb with southeasterly to easterly winds from the surface to 700 mb. This vertical structure is similar to soundings on the eastern edge of the mesoscale cyclonic vortex in AOP-1A and is again indicative of conditions associated with a stratiform rain region of a tropical MCS.

The vertical cross section of divergence along the east–west flight legs across 17°N (Fig. 14) indicate a

Fig. 6. Vertical cross section of divergence (solid is positive, negative is dashed; units of 10⁻³ s⁻¹) and zonal and vertical winds (see scale in upper right) along 16°N during AOP-1A.
region of sinking motion below strong midlevel convergence and a region of low-level divergence. In conjunction with the rising motion aloft, the stretching of columns is consistent with generation of a midlevel MCV. The vertical cross section of PV along 17°N (Fig. 15) does define a midlevel maximum between 500 and 600 mb and a narrow band of positive PV that extends downward and westward. Notice that the upward deflection of the potential temperature surfaces in this PV extension below 800 mb clearly indicate that the lower portion of the MCV is still cold core at this stage. Although a low-level circulation is clearly identifiable in the aircraft winds (Figs. 12b,c), this low-level cold-core structure and the low-level divergence maximum are not characteristics that would be conducive to low-level intensification and transformation to a warm-core circulation system.

It is hypothesized that the location of this circulation on the cyclonic shear side of the band of strong southerlies provides a favorable dynamic environment for the mesoscale circulation. Whereas the northern MCV in AOP-1B and the MCV in AOP-1A could not penetrate downward through the strong south-southwesterly flow that was directly beneath their midlevel centers, the southern MCV of AOP-1B existed over a favorable low-level environment that also contributed to the regeneration of convection along 15°N, which helped the MCV persist through the convective minimum period. The positive relative vorticity maximum at 750 mb near 139°E (Fig. 16) is lower than the PV maximum and appears to be associated with the downward extension of PV in Fig. 15. The positive relative vorticity region on the cyclonic shear side of the north-oriented confluent flow is believed to be more favorable for continued maintenance of the MCV. The remaining question is whether the southern MCV defined in AOP-1B could persist long enough to be related to the formation of TS Ofelia at 0600 UTC 25 July 1993 (ATCR 1993), which was 18 h after AOP-1B.

Fig. 7. Vertical cross section of potential vorticity (thick lines, $10^{-5}$ m$^2$ K s$^{-1}$ kg$^{-1}$) and potential temperature (thin lines, K) along 16°N during AOP-1A.

Fig. 8. Vertical cross section of divergence (solid is positive, negative is dashed; units of $10^{-8}$ s$^{-1}$) and meridional and vertical winds (see scale in upper right) along 141.5°E during AOP-1A.

Fig. 9. Skew $T$–lnp profiles as in Fig. 5 except for ODW 12 (15°N, 140.7°E), which was deployed at 0644 UTC 23 July 1993.
6. Formation of TS Ofelia

During the two AOPs, which spanned two consecutive daytime convective minimum periods, three MCVs were identified in the aircraft data. Two of the circulations were restricted to middle levels and were over the strong low-level south-southwesterly flow. No evidence was found that the circulation identified in AOP-1A persisted. Convection associated with the northern middle level circulation in AOP-1B continued to move northward before dissipating nearly 12 h after the AOP.

The southern circulation in AOP-1B was identifiable to 850 mb and was located in a dynamically favorable environment of cyclonic shear in the large-scale flow. It has already been noted that some deep convective cells were growing along the southern boundary of this circulation (Fig. 11). This convection continued to increase into the nighttime period (Fig. 17). Convection increased along 15°N (Fig. 17a), and the eastern cell moved northward as it continued to intensify (Figs. 17b–d). As this cell approached 17.5°N, a cyclonic rotation was evident to the west (Figs. 17e,f). At the end of the 10-h period (Fig. 17f), the convection seemed to rotate about a center that was near 17°N, 138.5°E. Shortly after daybreak (3 h after the time of Fig. 17f), a mesoscale cyclonic circulation was clearly revealed by curved cumulus bands in the 2230 UTC 24 July 1993 GMS visible imagery (labeled V Fig. 18a). Since the center of this vortex is just north of 17.5°N along 138.5°E, or about 1° latitude north of the apparent center of rotation of the convection in Fig. 17f, the center is estimated from the visible imagery to have moved northward at approximately 10 m s⁻¹.

Following the detection of the exposed mesoscale vortex at 2230 UTC 24 July (Fig. 18a), the vortex was accurately tracked in the hourly visible satellite imagery (Figs. 18b–d). Six hours after the initial detection, the first outbreak of deep convection that would lead to the formation of TS Ofelia at 20°N, 138°E (Fig. 18d) was detected along the northward track of the MCV. Therefore, the vortex moved northward at approximately 13 m s⁻¹ during this period. This convective outbreak occurred along the right side near the middle of the tightly curved cumulus lines. The cirrus shield above the erupting convection (Fig. 18d) appeared to spread almost uniformly in the horizontal. Within 4 h, cirrus had spread over the low-level cumulus lines and formed a central dense overcast. The fact that JTWC issued the first warning on this system at 0600 UTC 25 July 1993 with an estimated maximum wind of 30 kt is an indication of the rapid intensification characteristic of midget tropical cyclones.

During an AOP (AOP-2A) that was conducted approximately 18 h after the initial warning, aircraft observations indicated maximum winds near 50 kt. During this AOP, the cyclonic circulation at 500 mb was mostly confined within a 150-km radius (not shown).
Although the highly asymmetric structure of this rapidly moving cyclone makes a size estimate difficult. The central dense overcast also remained small during the observation period.

In summary, the outbreak of deep convection that eventually lead to the formation of TS Ofelia is well documented in the visible imagery. This convection develops in association with an MCV that is clearly depicted in visible imagery beginning at 2230 UTC 24 July 1993 (Fig. 18a). Based on the development and movement of convection identified in infrared satellite imagery (Fig. 17) between the end of AOP-1B and the presence of the visible circulation at 2230 UTC 24 July 1993, it is concluded that the circulation observed in the AOP-1B flight data along 17°N is the precursor to the formation of TS Ofelia. Although a cold pool (Fig. 15) and low-level divergence (Fig. 14) were found beneath the southern MCV in AOP-1B, the circulation existed on the strong cyclonic shear side of the large-scale north-oriented confluent flow. This favorable dynamic environment aided in the development and maintenance of the circulation at 700 mb and below. The initiation of convection along the southern portion of the vortex, which was probably due to enhanced low-level confluence between the MCV circulation and the large-scale flow, contributed to the maintenance and intensification of the vortex during the period following AOP-1B.

One unexplained aspect of the formation of TS Ofelia concerns the source of the clear region in which the low-level circulation became visible (Fig. 18a). The lack of convection near the center of the low-level circulation suggests that either upper-level shear is very deep or there is strong subsidence over the vortex. Subsidence could result from the outflow of the convection that had taken place overnight (Fig. 17) to the south of the exposed vortex meeting upper-level winds from around the TUTT cell to the east. Strong subsidence could contribute to a strong low-level inversion under which convective potential would build before an eventual release into explosive convection. Because the upper-level shear had been neutralized during the period of strong subsidence, the convection could grow vigorously and give rise to the circular cirrus shield.

7. Summary and discussion

Two AOPs were conducted within an area of persistent deep convection that was forced by large-scale, low-level, north-oriented confluent flow between a monsoon gyre to the west and a strong subtropical ridge to the east. Each AOP was conducted during a daytime minimum in deep convection that followed a period of enhanced convection during the previous night. During the two AOPs, three MCVs (Fig. 19) were defined in aircraft flight-level and dropwindsonde winds. The
MCV observed during AOP-1A and the northern MCV observed during AOP-1B were well-defined midlevel circulations that were directly above the strong north-oriented flow that was concentrated at 850 mb and below. During the convective minimum periods of AOP-1A and AOP-1B, both of these MCVs weakened. No evidence could be found in satellite imagery that AOP-1A persisted much beyond the end of the AOP. By contrast, a weak convective signature associated with the northern MCV of AOP-1B was tracked for nearly 12 h following the AOP (Fig. 19). This small convective cell, which tracked steadily northwestward, did not intensify and eventually dissipated. The lack of persistence of these MCVs is attributed in part to the location of the midlevel center directly over the strong low-level flow. Therefore, once convection decreased, which is associated with a decrease in the physical mechanisms that generate and maintain the MCV, the MCV was unable to tap into low-level energy sources.

The midlevel PV maximum of the southern MCV during AOP-1B was located near 550 mb, and there was a weak extension downward to 850 mb. Beneath the midlevel center, the environment was cold and downward motion existed below a midlevel convergence maximum. Dropwindsonde profiles of temperature and dewpoint indicate an environment that is typically associated with stratiform rain regions of tropical MCSs. The primary difference between this MCV and the MCV of AOP-1A and the northern MCV in AOP-1B is its location on the cyclonic shear side of the large-scale low-level flow provided a favorable dynamic background field. Ritchie (1995) found that in simulations of midlevel MCVs, downward extension of the midlevel center occurred when the MCV existed in a
large-scale background field of positive vorticity. In this case, the low-level circulation associated with the MCV also contributed to renewed convection along the periphery of the MCV at a time when the large-scale convection was decreasing over the broad area. This increase in convection most likely contributed to the persistence of the MCV through the convective minimum period. Following the AOP, the convection increased and was observed to rotate in a cyclonic manner. The track of this southern area of convective ac-

Fig. 13. As in Fig. 5 except for ODW 1 (17°N, 138.3°E), which was deployed at 0442 UTC 24 July 1993 during AOP-1B.

Fig. 14. Divergence, zonal, and vertical winds as in Fig. 6 except for AOP-1B along 17°N.

Fig. 15. Potential vorticity and potential temperature as in Fig. 7 except for AOP-1B along 17°N.

Fig. 16. Vertical cross section of relative vorticity (positive is solid, negative is dashed; units of 10^{-4} s^{-1}) along 17°N during AOP-1B.

tivity (Fig. 19) is consistent with the positions of a low-level circulation that were evident in visible satellite imagery 15 h following the center time of AOP-1B. The track and convection associated with the low-level center were identifiable in hourly visible satellite images (Fig. 18). The first official tropical cyclone warning on the system was made 8 h following the initial detection of the low-level circulation.

The above observations and interpretations may then be examined in terms of conditions that are related to the development of a mesoscale feature into a tropical cyclone and the influence of the large-scale environment on that development. A basic hypothesis of the Tropical Experiment in Mexico (TEXMEX) during 1991 (Emanuel 1993) was that the dry midlevel
Fig. 17. Geostationary satellite infrared imagery for the indicated times between (a) 0930 UTC 24 July and (f) 1930 UTC 24 July 1993. The arrow in each panel points to the convection associated with the southern MCV during AOP-1B.
conditions typically found in the Tropics must be transformed into a layer of relatively moist air. Their physical explanation was that deep convection in the presence of the typical dry midlevel air will be accompanied by convective-scale downdrafts that will introduce air with low equivalent potential temperature ($\theta_e$).
Fig. 18. Geostationary visible imagery at indicated times. Arrow points to the low-level circulation from which TS Ofelia formed. The "V" in (a) corresponds to the "V" in Figs. 1 and 19.

into the subcloud layer, which would stabilize the near-surface air and inhibit further convection. The TEX-MEX hypothesis is that either strong surface winds are required to evaporate moisture from the ocean to overcome the downdraft stabilization, or an increase in $\theta_e$ of the midlevels is required to prevent introduction of low-$\theta_e$ air into the subcloud layer. The dropwindsonde profiles (e.g., Fig. 13) close to the center of the southern MCV of AOP-1B indicate that a warm, dry layer exists in the mid- to lower troposphere at that time. Although no soundings are available in the MCV on the day of Ofelia's formation, continuation of the warm, dry layer might be expected owing to the lack of deep convection, which was presumably caused by a region of subsidence, when the low-level circulation became visible. It is possible that the MCV observed during AOP-1B gradually deepened to the surface during the 12 h prior to detection of the low-level circu-
Fig. 19. Tracks of MCVs during and following AOP-1A and AOP-1B. The solid rectangle (AOP-1A) and the solid circles (AOP-1B) are the positions defined by aircraft observations. The open circle and "X" are positions defined by satellite imagery. The "V" defines the low-level circulation center that is also labeled with a "V" in Figs. 1 and 18a. The hurricane symbol defines the position where the first tropical cyclone warning was issued by JTWC. Times are dd/hh (UTC).

lation, which would enable air–sea fluxes to increase the convective potential of the subcloud layer until release near the center of the low-level circulation.

An alternative hypothesis has been proposed by Tripoli (1995, personal communication) based on simulations with a nonhydrostatic model. Tripoli suggests that a central dry region, which seems to be present in the visible low-level circulation (Fig. 18a), becomes the area for concentrated subsidence of the air rising in curved convective lines that surround the central region. That is, this dry, subsidence region becomes an eyelike feature about which the mesoscale cyclonic circulation intensifies. In this case, convection would increase along the curved bands of cumulus clouds that surround the central region of subsidence.

During the period when the low-level circulation was evident in visible imagery (Fig. 18), there is some indication that convection was being initiated very near the center on the eastern side of the circulation (Fig. 18b). However, the small scale of the low-level circulation that eventually became TS Ofelia, and the rapid development of the deep convection that eventually covered the low-level lines of cumulus, make it difficult to determine exactly where the initial eruption of deep convection occurred.

One favorable environmental dynamical condition for tropical cyclone formation is cyclonic absolute vorticity. Tropical Storm Ofelia formed near 20°N, which is well away from the equator so that the Coriolis parameter is relatively large. As discussed above, the southern MCV in AOP-1B, which eventually becomes TS Ofelia, existed on the cyclonic shear side of the large-scale confluent flow. Because the monsoon gyre cyclonic shear zone is rather concentrated, this may be a plausible explanation for the continued small horizontal extent of the tropical cyclone.

Another favorable environmental condition for tropical cyclone formation is small vertical shear of the horizontal wind (Frank 1987). The typical upper-tropospheric winds in the TS Ofelia formation area are northeasterlies as air flows equatorward from a northward displaced subtropical ridge over eastern Asia and the western North Pacific. In the Ofelia case, these northeasterlies are enhanced by the presence of the TUTT cell to the northeast and TY Nathan to the north. These strong upper-level northeasterlies had three notable effects. First, the cirrus associated with the deep convection in the monsoon gyre streamed rapidly to the southwest. Second, the northern edge of the cirrus shield was displaced southward during each daytime convective minimum, which exposed the low-tropospheric circulations. Third, the superposition of the upper-level northeasterlies over the monsoon gyre southwesters imposed a larger vertical wind shear than is considered permissible for tropical cyclone formation. Satellite imagery during the 12-h period following AOP-1B suggests that the strongest upper-level northeasterlies were displaced east of the region of deep convection as the low-level confluent flow moved westward, which increased the separation between the convective area and the TUTT cell to the east. At this time, TY Nathan had moved far to the north and was no longer influencing the region. The reduction in upper-level northeasterlies may have contributed to the subsidence over the low-level center in the visible imagery by allowing some outflow from the deep convection to the south to move northward and impinge on the weakened northeasterlies to cause subsidence over the low-level center. These conditions would significantly reduce the large vertical wind shear that had existed over the region.

These observations from the two AOPs conducted in a region of enhanced deep convection, and satellite imagery of conditions following the second AOP, indicate that the small TS Ofelia formed from one persistent MCV. It is clearly necessary to better specify suitable environmental conditions that contribute to the persistence of the MCV. Without in situ aircraft observations on the formation day, it is unclear whether dry, midtropospheric air was actually overcome (or not overcome) by enhanced air–sea fluxes (TEXMEX hypothesis), or how the central dry area became a concentrated area of subsidence (Tripoli hypothesis). Observations from AOP-1B appear to indicate that the persistence of the southern MCV was due to its extension to low levels, which may be related to its location within the cyclonic shear of the large-scale confluent flow. These conditions apparently contributed to the survival of the southern MCV through the convective minimum period, when the other two MCVs without a downward extension did not survive. Although this is a single case study, it provides some unique observations and insights into one type of midget tropical cyclone formation. Additional observations and numerical simulations are needed to understand the thermodynamic and dynamical processes, and to develop
appropriate techniques that use satellite imagery to monitor these formations.

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