Vertical Wind Shear Influences on Tropical Cyclone Formation and Intensification during TCM-92 and TCM-93

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ABSTRACT
Vertical wind shears between 200 and 850 mb are calculated from operational analyses and special interactive analyses for Tropical Storm Steve during the Tropical Cyclone Motion (TCM-93) field experiment and for Typhoon Omar at the end of the TCM-92 experiment. The operational Fleet Numerical Meteorology and Oceanography Center (FNMOC) analyses have strong 200-mb winds crossing over the intensifying storms, which leads to vertical wind shears exceeding the 12.5 m s⁻¹ threshold value believed to prevent tropical cyclone intensification. Interactive analyses are produced with the multiquadrilateral interpolation technique that blends composited cloud-drift winds and aircraft reports between 1800 and 0000 UTC and between 0600 and 1200 UTC, sets of synthetic observations to represent missing or mislocated tropical circulations, and the FNMOC analyses that are used as a first-guess field. These interactive analyses indicate that the high winds at 200 mb associated with low-latitude circulations such as monsoon depressions or other tropical cyclones that appear to be impinging on Steve and Omar are actually deflected around the convective outflows. Vertical wind shears calculated from the interactive analyses are well below the threshold vertical wind shear value, which is consistent with the observed intensification of Steve and Omar. In seven of the nine Steve analyses, the insertion of the composite observations alone resulted in deflected flow around convective outflow, so that the reduced shears are not an artifact of synthetic observation insertions. It is hypothesized that the large vertical wind shears associated with the low-latitude circulations may actually be concentrated in a shallow layer that may be opposed and deflected by a similar shallow layer of convective outflow above developing and intensifying tropical cyclones. In that case, an understanding of the role of vertical wind shear and prediction of tropical cyclone intensification may require special analyses of the type developed following the TCM-93 experiment.

1. Introduction

One of the six favorable environmental factors (Gray 1968, 1975) for tropical cyclone development is vertical wind shear below some threshold value. This requirement was included in early formation forecast checklists (e.g., Simpson et al. 1969) and is included in a recent global guide for forecasting tropical cyclones (Holland et al. 1993). Support for this minimum vertical wind shear requirement is found in McBride and Zehr (1981). As McBride (1995) recently summarized, the minimum vertical wind shear may be in a small area directly over the tropical cyclone that is sandwiched between adjacent areas of large vertical wind shear.

Because tropical data sources tend to be at upper levels (especially satellite cloud-drift winds and jet aircraft reports) and lower levels (satellite cloud-drift winds and surface reports extrapolated upward), the vertical wind shear is often expressed as the 200-mb-minus-850-mb wind difference. Over the tropical oceans where tropical cyclones typically form and intensify, few rawinsondes (or other data sources) are available to define the vertical wind shear in more detail.

Whereas the Gray (1968, 1975) and the McBride and Zehr (1981) studies were based on composites of rawinsondes from many tropical cyclones, the operational forecaster must rely on subjective (hand-drawn) or objective analyses to estimate the vertical wind shear. Often the thick cirrus over the formation area prevents calculations of cloud-drift winds at either upper or lower levels, and it is only on the periphery of the developing or intensifying tropical cyclones that satellite cloud-drift winds are available.

Zehr (1992) used the Australian Bureau of Meteorology real-time analyses to estimate a threshold vertical wind shear of 12.5 m s⁻¹ beyond which western North Pacific Ocean tropical cyclones did not form. DeMaria et al. (1993) derived statistical relationships between the intensity changes of Atlantic tropical cyclones and the vertical wind shear between 200 and 850 mb. As expected, these shear values (calculated from real-time objective analyses on a 1° latitude-longitude
grid) are negatively correlated with intensity changes. However, the explained variance is only about 15%.

Although the primary purpose of the Tropical Cyclone Motion (TCM-92 and -93) field experiments was to document the effect of Mesoscale Convective Systems on cyclone motion, the formation and intensification stages were continually monitored with hourly, high-resolution Geostationary Meteorological Satellite (GMS) visible and infrared imagery. During these experiments, two tropical cyclones [Tropical Storm (TS) Steve 1993, and Typhoon (TY) Omar 1992] had periods in which strong upper-level winds in the Naval Operational Global Atmospheric Prediction System (NOGAPS) analyses (Goerss and Phoebus 1992) from the Fleet Numerical Meteorology and Oceanography Center (FNMO) were impinging on the storms. Nevertheless, Steve intensified from a disturbance to a tropical depression (TD) and tropical storm. Although Omar's intensification was slowed and a slowing and small poleward deflection occurred during the period with strong winds aloft (JTWC 1992), the effect of the large vertical wind shear implied by the NOGAPS analyses was not as unfavorable to tropical cyclone formation and intensification as expected from prior research studies and forecaster rules.

The objective of this paper is to demonstrate that real-time tropical wind analyses may not yield realistic vertical wind shear values in the regions of forming and intensifying tropical cyclones. Two periods of operationally analyzed large vertical wind shear are reexamined with interactive analyses of the observations and conceptual models that are analogous to the subjective analyses prepared during TCM-93 (Carr and Jeffries 1993). Based on the interactive analyses, the formation of TS Steve occurred under vertical wind shear values well below the threshold values of Zehr (1992). Thus, special wind analyses as in TCM-92 and -93 may be required to understand (and to forecast) tropical cyclone formation and intensification.

2. Interactive analyses

A full description of the interactive analysis technique is given in Jeffries (1995). Three key components of the technique will be briefly described here: (i) composite observations; (ii) complete sets of synthetic observations; and (iii) a multiquadric interpolation (MQI) technique that draws closely to the wind observations and provides values on a regular 1° latitude-longitude grid. The analysis is interactive as intermediate analyses are produced and evaluated when the composite observations are added, when the sets of synthetic observations are inserted, and as point synthetic observations are added as necessary to fine tune the final analyses.

a. Data compositing

As during TCM-93 (Carr and Jeffries 1993), 6-h sets of observations are composited between 0600 and 1200 UTC and between 1800 and 0000 UTC to produce analyses that are effective at 0900 and 2100 UTC. Because the cloud-drift winds are calculated at the endpoints of these compositing periods, the number of these winds is typically doubled compared to the usual procedure of 6-h datasets centered on the synoptic times. Cloud-drift winds between 300 and 150 mb are all considered as 200-mb winds, and the analyst is required to quality control unrepresentative values. Aircraft records above 10 060 m (33 000 ft) are assumed to apply at 200 mb and are also time composited as above. The better data coverage over the ocean areas provides more confidence in the analyses, and many key changes in the interactive analyses arise from this step alone.

b. Sets of synthetic observations

As indicated previously, the presence of thick cirrus over developing tropical cyclones often prevents cloud-drift wind estimates at either the upper or lower levels. Aircraft also may be diverted around the tropical cyclones. Consequently, observations may only be available around the periphery of tropical cyclones, which makes it difficult to calculate the vertical wind shear.

Jeffries (1995) describes in detail the conceptual synoptic models from which the sets of synthetic observations are generated to represent the missing (or misplaced) tropical circulations. The tropical cyclone synthetic observations are derived from

\[ V = \frac{M}{r^{\pi}} - \frac{1}{2} f_0 r, \]

where

\[ M = \frac{1}{2} f_0 R_0^{1+x}, \]

and

\[ U_L = -0.4V, \]

\[ U_U = U_{\text{max}} \left( \frac{r_{\text{max}}}{r} \right). \]

Here \( V \) is the tangential wind at either the upper level \((x = 1.0)\) or the lower level \((x = 0.4)\), \( r \) is radius, \( f_0 \) is the Coriolis value at the latitude of the storm, \( R_0 \) is the maximum storm extent, \( U_L \) and \( U_U \) are the radial winds at the lower and upper levels. The \( U_{\text{max}} \) at upper levels in (3) is calculated to satisfy mass balance with the maximum low-level inflow represented by \( U_L \). Even weak tropical waves may be represented at lower levels based on (1) and (2) by selecting appropriate values of \( U_{\text{max}} \) and \( r_{\text{max}} \). In both cases, the winds from (1) and (2) are superposed on a background flow equal to the system translation speed over the past 12 h.

The outflow above tropical cloud clusters often takes the form of a point mass source that turns anticyclon-
ically at larger radii. Based on a series of test analyses, sets of synthetic observations are generated from (3) by typically setting $U_{\text{max}} = 15$ m s$^{-1}$ and $r_{\text{max}} = 100$ km. The anticyclonic turning is achieved by setting $M = 0$ and $x = 1.0$ in (1). A background flow equal to the cloud cluster translation is added to these wind components.

A tropical upper-tropospheric trough (TUTT) cell is represented by a set of synthetic wind observations at 200 mb from

$$ V = \frac{V_{\text{max}}}{2} \left[ 1 - \cos \left( \pi \frac{r}{r_{\text{max}}} \right) \right], $$\hspace{1cm} (4)

and

$$ U = -0.4V. $$\hspace{1cm} (5)

Here $V_{\text{max}}$ is the estimated maximum tangential wind at a radius $r_{\text{max}}$ from animated GMS imagery, adjacent aircraft reports, or rawinsondes. These winds are considered to be a perturbation on a background flow equal to the translation speed of the TUTT cell and are assumed to decrease to zero at $r = 2r_{\text{max}}$.

An upper-level anticyclone is created from (4) and (5) by simply changing the signs. This option is seldom used in these interactive analyses.

These complete sets of synthetic observations are primarily intended to represent tropical circulations that are evident in satellite imagery but are missing or are mislocated in the objective analysis. In each case, a minimal set of synthetic observations is desired that is properly located and will blend smoothly into the adjacent real observations. Because the analyses are on a relatively coarse 1° latitude–longitude grid, these sets of synthetic observations are not intended to represent the actual circulations in great detail.

**c. Multiquadric interpolation (MQI)**

As described by Nuss and Tittley (1994), the MQI technique fits surfaces through all the observations so that values may be interpolated on the 1° latitude–longitude grid. In this interactive application, the first-guess field is the NOGAPS objective analyses that have been interpolated to either 0900 or 2100 UTC. All real or synthetic wind observations are entered as increments to this first-guess field. As the final MQI analysis is then the addition of these interpolated increments to the first-guess field, areas without any observations revert back to the NOGAPS analysis.

Because this is an interactive analysis in which the analyst does the quality control, almost all observations are accepted. Only observations that are more than five standard deviations from the corresponding first-guess value at that point are rejected. The closeness of the surface fit to the observations in the MQI technique is specified by a smoothing parameter. Sensitivity tests for the smoothing parameter (see Jeffries 1995) resulted in a value of 0.005. With a larger smoothing value of 0.01, the MQI analysis did not draw closely to the rapidly varying wind observations around tropical circulations. A smaller (0.001) smoothing value results in a MQI analysis that fits the observations so closely that closed or unrepresentative circulations are drawn around weak or noisy winds. Based on these sensitivity tests for the smoothing parameter, the MQI technique results in streamlines that fit the wind observations similar to an expert subjective analysis.

3. Tropical Storm Steve

The interactive analysis procedure was first tested for a few analyses containing TS Steve, which developed in the wake of TY Robyn. The pre-Steve disturbance was detected as a cyclone circulation near 8°N, 154°W at the eastern end of a monsoon trough (JTWC 1993). This disturbance initially moved north-northeastward and then northwestward under the combined influence of the monsoon trough and TY Robyn. A set of 850 and 200 mb interactive wind analyses was produced from 2100 UTC 3 August (shortly after the disturbance was detected) to 2100 UTC 7 August, when TS Steve had 45-kt (22 m s$^{-1}$) winds. Vertical wind shear fields will be calculated from these nine sets of interactive analyses and compared with shear fields from the real-time NOGAPS analyses that served as the first-guess fields.

Jeffries (1995) describes the step-by-step interactive analyses for each of the nine sets of 850- and 200-mb MQI analyses. Only two of these times will be presented here to illustrate characteristic features of the interactive MQI analyses.

**a. Analyses at 2100 UTC 4 August 1993**

Common problems with the real-time NOGAPS analysis (Fig. 1a) are: (i) no representation of the upper-level outflow from TY Robyn near 12.3°N, 140.1°E; and (ii) absence of a point outdraft around 11°N between 150° and 160°E from the convection east of Robyn. Whereas the satellite imagery (Fig. 2) has a pronounced cloud boundary along the poleward edge of this convection, the NOGAPS analysis that is the first-guess field (Fig. 1a) for the MQI analysis has a meridional flow between 150° and 165°E that extends from 35°N to the equator. Although animation of the GMS imagery clearly indicates zonal wind components along the convergent asymptote (defined as an elongated streamline along which two opposing flows are converging) that is consistent with the two 30-kt (15 m s$^{-1}$) eastward wind observations at 15°N, 152°E and 15°N, 158°E, the first-guess analysis has meridional flow through this region. Either the quality-control step at FMNOC has rejected these two observations or the four-dimensional data assimilation has given too much weight to the short-term numerical model forecast that serves as the background field.
The first step in the interactive analysis of simply adding the composite observations from 1800 UTC 4 August to 0000 UTC 5 August (Fig. 1b) markedly changes the 200-mb analysis so that it is consistent with the presence of a convergent asymptote and the two rejected wind observations. An area near 11°N, 147.5°E of upper-level outflow in a spiral convective band associated with Typhoon Robyn and a point outflow near 15°N, 150°E are supported by the composite observations. It is suggested that these features are most pronounced near the end of the diurnal deep convection maximum around 1800 UTC. For reasons that are not clear, the NOGAPS analysis does not give the proper weight to these 1800 UTC cloud-drift winds. At the 0000 UTC synoptic time, the diurnal convective minimum is approaching and the indications of the convective system in the cloud-drift winds are reduced. Of course, the MQI technique is tuned to draw closely to these observations and a convergent asymptote appears (Fig. 1b) along 16°N between 140° and 150°E between the convective outflows and the meridional flow farther poleward.

Since no feedback from the MQI analyses to the next NOGAPS analysis occurs, subsequent NOGAPS analyses continue to have meridional flow through this region of convection associated with Typhoon Robyn and pre-Steve. It is emphasized that in seven out of these nine analyses the insertion of the composite observations alone resulted in a convergent asymptote between the convective outflows and the meridional flow farther poleward. That is, it was only necessary to use the point outdraft set of synthetic observations in (1) and (3) in two of the nine analyses. In the case of Fig. 1c, the set of synthetic observations was used only to reposition the point outdraft to a position that agreed better with the satellite imagery interpretation.

A common problem in all nine of the 200-mb analyses was the absence of a well-defined representation of the outflow from tropical cyclones. As indicated above, this data void is related to the absence of cloud-drift winds except on the periphery of thick cirrus regions, the diversion of aircraft around tropical cyclones, and few rawinsondes near strong tropical cyclones. The FNMOC tropical cyclone synthetic observations are only entered between 400 and 1000 mb (Goerss et al. 1991). Satellite imagery (and the official Weather Advisory) indicates that TY Robyn has 70-kt (35 m s⁻¹) maximum winds and is moving west-northwest (320°) at 7 kt (3.5 m s⁻¹), and the size of the overall convective area suggests an outer radius $R_o = 800$ km. Using these values in (1) and (2) with a synthetic observation cutoff radius $r_{cut} = 200$ km results in a set of nine synthetic observations to represent TY Robyn near 12.2°N, 140.1°E in Fig. 1c. The $r_{cut}$ value is generally specified as approximately one-half of the distance to the surrounding observations. Another set
of nine synthetic observations to reposition the point outdraft near 13°N, 150°E is developed using the typical values of 15 m s\(^{-1}\) outflow at 100 km and a \(r_{\text{cut}}\) of 200 km. Inclusion of these sets of synthetic observations successfully represents the upper-level outflow of TY Robyn and the proper position of the point outdraft.

An illustration of the third (fine-tuning) step in the interactive analysis is given in Fig. 1d. A line-divergence region has been analyzed in Fig. 1c near a calm wind observation at 7°N, 133°E and the closed circulation near Mindanao Island in the southern Philippines should be depicted as an open diffusent wave. After four iterative analyses, the set of seven-point synthetic observations highlighted in Fig. 1d is found to represent properly the 200-mb circulations and eliminate the effects of the bad observation near 7°N, 133°E. Insertion of point synthetic observations is the most time-consuming aspect of the interactive analysis, which is why complete sets of synthetic observations have been developed to represent the various tropical circulations (section 2b).

The corresponding 850-mb analysis begins from the first-guess (real-time NOGAPS) analysis in Fig. 3a. Notice that only two observations are available within 8° latitude and 10° longitude of TY Robyn, which is thus primarily represented by the FNMOC synthetic observations. Especially as tropical cyclones become more intense, the outer circulation represented by the FNMOC synthetic observations appears to be too strong. Thus, a set of synthetic observations (Fig. 3b) is developed from (1) and (3) with a radial cutoff of \(r_{\text{cut}} = 300\) km. Two weak low-level circulations are also inserted as sets of five synthetic observations using \(V_{\text{max}} = 15\) kt (7.5 m s\(^{-1}\)), \(r_{\max} = 100\) km, and \(r_{\text{cut}} = 150\) km. The combination of the composite observations and the sets of synthetic observations results in a proper depiction of all circulations inferred from the satellite imagery. The vector wind differences (Fig. 3c) between the final MQI analysis (Fig. 3b) and the first-guess field (Fig. 3a) indicate that significant (>5 m s\(^{-1}\)) modifications have been made near TY Robyn. Stronger cyclonic winds are analyzed just north of the center, and the easterly wind differences to the south of Robyn indicate the FNMOC synthetic winds at outer radii are too strong in this data-void area. The smaller 850-mb winds around Robyn in the MQI analysis will also affect the vertical wind shear calculations to be described below.

**b. Analyses at 2100 UTC 6 August 1993**

As in the previous analyses, major adjustments to the first-guess field (Fig. 4a) at 200 mb are required, which may be due in part to the lack of over-ocean observa-
Fig. 3. Streamline analyses at 850 mb for 2100 UTC 4 August of (a) first-guess field with real-time rawin-
sondes and cloud-drift winds at 0000 UTC 5 August superposed; (b) final MQI analysis blending first-guess
field, composite cloud-drift winds at 1800 UTC 4 August and 0000 UTC 5 August plus sets of synthetic
observations for TY Robyn near 12°N, 140°E and pre-Steve near 10°N, 158°E; and (c) vector differences
exceeding 5 m s⁻¹ of final MQI analysis in (b) minus first-guess field in (a).
Fig. 4. Streamline analyses at 200 mb for 2100 UTC 6 August of (a) first-guess field similar to Fig. 1a; (b) final MQI analysis as in Fig. 1c with TY Robyn near 19°N, 134°E and TD Steve near 15°N, 149°E; and (c) vector differences exceeding 5 m s⁻¹ of final MQI analysis in (b) minus first-guess field in (a).
tions received in real time at FNMOC. Inclusion of the composite observations and sets of synthetic observations to represent TY Robyn near 19°N, 135°E and TD Steve near 13.5°N, 149.5°E markedly change the analysis (Fig. 4b). Based on the official Weather Advisory, TY Robyn has maximum winds of 100 kt (50 m s\(^{-1}\)), and TD Steve has maximum winds of 30 kt (15 m s\(^{-1}\)) and a motion vector of 290° at 8 kt. Based on persistence and the continued presence of convection southeast of Robyn, an upper-level anticyclone with \(V_{\text{max}} = 25 \text{ kt (12 m s}^{-1}\)), \(r_{\text{max}} = 100 \text{ km, and } r_{\text{cut}} = 150 \text{ km is entered. The combination of these three sets of synthetic observations blends well with the meridional wind observations between 140° and 146°E from 20° to 8°N (compare Figs. 4b and 4a) and properly represents convergent asymptotes to the north of both Robyn and Steve that are revealed in the satellite imagery (Fig. 5).

Vector wind differences (Fig. 4c) between the final MQI analysis and the first-guess field indicate the effects of inserting the outflows from Robyn and Steve. In addition, major changes in the wind field in the northeast corner of the domain and westerly difference vectors over the Philippine Sea are introduced primarily by the composite observations alone. Such large differences evidently occur in this example because the NOGAPS analysis that is used here as a first-guess field (Fig. 4a) is almost devoid of observations over the ocean. In those areas, the short-term model forecast was probably the only input to the NOGAPS analysis. Compositing the observations over the 1800 and 0000 UTC periods as in these MQI analyses assures that some real observations are available if a single missed transmission of satellite cloud-drift winds occurs.

Insertion of synthetic observations in the 850-mb analysis is necessary around TY Robyn where cirrus has prevented any low-level cloud-drift winds and for TD Steve near 13.5°N, 149.5°E, which is not represented in the first-guess field (Fig. 6a). Because of the large data void around Robyn, a \(r_{\text{cut}} = 500 \text{ km is used, which results in a set of 59 synthetic observations (Fig. 6b). In addition to producing a more compact circulation for Robyn, the MQI analysis blends more smoothly with the surrounding real observations. The MQI analysis also has a small closed cyclonic circulation around TD Steve in a region that the first-guess field (Fig. 6a) had only weak cyclonic curvature. The major contributor to the vector difference (Fig. 6c) between the final MQI analysis (Fig. 6b) and the first-guess field (Fig. 6a) is the excessive outer cyclonic circulation in the FNMOC representation of TY Robyn. Whereas the first-guess (NOGAPS) field has meridional flow east of Robyn that extends from the equator to 40°N, the MQI analysis has a more compact (but still rather large) TY Robyn and a westerly flow along 30°N between 130° and 155°E.

![Fig. 5. GMS infrared image at 2030 UTC 6 August 1993.](image-url)
m s⁻¹) are calculated over TD Steve (and also over TY Robyn) in the first-guess (NOGAPS) analyses. By contrast, the MQI analyses result in a vertical wind shear of around 10 kt (5 m s⁻¹), which is more consistent with the observed intensification of Steve to a TS in the next 12 h. The critical difference arises from the 200-mb winds that cross over TD Steve in the first-guess field (Fig. 4a) but are deflected around Steve in the MQI analysis (Fig. 4b). The satellite image (Fig. 5) has a bow wave between the outflow from Steve and the northerly winds that are present farther north, which supports deflection of these winds around Steve as in the MQI analysis. Whereas an intensity forecast based on the first-guess (NOGAPS) vertical shear would be for constant or decreasing maximum speeds, the smaller shears in the MQI analyses would be consistent with the observed intensification of Steve.

c. Vertical wind shear over TS Steve

The 200–850-mb vertical wind shear averaged over the gridpoint values within 333 km of the position of TS Steve are calculated from the first-guess (NOGAPS) fields and from the final MQI analyses (Fig. 8). The vertical wind shears are compared with the Zehr (1992) threshold value of 12.5 m s⁻¹, beyond which tropical disturbances did not develop. During the earliest stages of Steve, strong northerlies on the trail-
ing side of a TUTT cell to the northeast appeared to be impending on the development area. In the NOGAPS analysis (Fig. 1a), these meridional winds are continued to the equator, which results in vertical shear values exceeding the Zehr threshold at 2100 UTC 3 August and 0900 UTC 4 August (Fig. 8). However, the composite observations and synthetic observations based on the satellite imagery (Fig. 2) indicate that a convergent asymptote exists between the large-scale meridional flow and the outflow from the convection associated with Ty Robyn, the monsoon trough, and the pre-Steve disturbance. Thus, the final MQI analysis (Fig. 1d) that draws closely to these observations produces a vertical wind shear of only 5 m s$^{-1}$ at 0900 UTC 4 August (Fig. 8). According to the post-storm analysis (JTWC 1993), the pre-Steve disturbance intensified from 15 kt (7.5 m s$^{-1}$) at 2100 UTC 3 August to 30 kt (15 m s$^{-1}$) at 1200 UTC 5 August. Clearly, the small vertical shear values from the MQI analyses are more consistent with the pre-Steve intensification than are the shears from the NOGAPS analyses.

Both the NOGAPS and the MQI analyses have small vertical wind shears at 0900 5 August (Fig. 8). Given the ±5 kt (2.5 m s$^{-1}$) discrete values in the recording of storm intensities, the pre-Steve disturbance either remained constant or increased by only 5 kt until 2100 UTC 6 August.

A second period of apparent large shear in the NOGAPS analyses occurs after 0900 UTC 6 August (Fig. 8). For example, the 200-mb NOGAPS analysis at 2100 UTC 6 August (Fig. 4a) has strong northeasterly winds across the TD Steve position. However, inclusion of the composite and synthetic observations in the final MQI analysis (Fig. 4b) indicates that these northeasterly winds are deflected around TD Steve, with a bow wave at the intersection with the outflow above Steve. Consequently, the vertical shear above Steve from the MQI analyses is about 6 m s$^{-1}$ (Fig. 8), compared to a value of about 15 m s$^{-1}$ from the NOGAPS analyses. According to JTWC (1993), tropical storm intensity of 35 kt (17.5 m s$^{-1}$) was achieved around 0600 UTC 7 August 1993. At this time, the NOGAPS vertical shear clearly exceeds the Zehr threshold and the MQI value is about 8 m s$^{-1}$. Again, the MQI values appear to be more consistent with the observed intensification of TS Steve than are the NOGAPS analyses.

4. Typhoon Omar analyses

A detailed description of the individual 200- and 850-mb interactive analyses for the TY Omar case will not be given because of the similarity to the TS Steve case. Rather, a summary of the first-guess fields and final MQI analyses at 200 mb for four days is given in Fig. 9. Two key upper-level synoptic features in the first-guess (NOGAPS) analyses during the first three days (Figs. 9a, 9c, and 9e) are: (i) an anticyclonic outflow over a large monsoon depression that developed into TS Polly; and (ii) a large TUTT cell that moved from about 20°N, 168°E (Fig. 9a) to near 25°N, 153°E (Fig. 9e), which is a translation speed of about 6 m s$^{-1}$. Although the NOGAPS analyses typically mislocate by about 5° latitude the centers of the TS Polly outflow inferred from the satellite imagery, the circulation is so large that this mislocation is not a serious problem. In the NOGAPS analyses (Figs. 9a, 9c, and 9e) that are the first-guess fields for the MQI analyses, the meridional flow between the anticyclone above TS Polly and the TUTT cell to the east crosses over the intensifying TS Omar. Except for one time, the corresponding NOGAPS vertical wind shears exceed the Zehr (1992) threshold of 12.5 m s$^{-1}$ from 0900 UTC 24 August to 0900 UTC 27 August (Fig. 10). During this period, Omar intensifies from 25 kt (12 m s$^{-1}$) to 70 kt (35 m s$^{-1}$), which is certainly inconsistent with expectations based on the NOGAPS vertical shears.

Only a selection of the final MQI analyses at 200 mb are provided in Fig. 9. In several of these analyses, insertion of the composite observations alone produces a more realistic depiction of the deflection of the impending flow around TY Omar (Fig. 9b). In other cases (Figs. 9d, 9f, and 9h), sets of synthetic observations inserted to represent the Omar outflow layer blend well with the adjacent real observations. The resulting MQI vertical wind shears (Fig. 10) are generally about 6–8 m s$^{-1}$ throughout the period, which is more consistent with the observed intensification of Omar. According to the post-storm analyses by JTWC (1992), the rate of intensification and the translation speed of Omar decreased from about 1800 UTC 25 August to about 1200 UTC 27 August. A rapid intensification from 75 kt (37 m s$^{-1}$) to 115 kt (57 m s$^{-1}$) then occurred in the next 24 h. In addition, the trans-
lation speed increased from 4 kt (2 m s$^{-1}$) to 8 kt (4 m s$^{-1}$) and Omar struck Guam and caused great damage (JTWC 1992). The diminishing of the meridional flow impinging on Omar is evident in Figs. 9f and 9h. In addition, opening of a second outflow channel toward the east and then poleward in the MQI analysis (Fig. 9h) is consistent with the observed rapid intensification. By contrast, the NOGAPS analysis (Fig. 9g) has the origin of the outflow mislocated well to the east of Omar so that large vertical wind shear (Fig. 10) from the east is analyzed.

5. Discussion

These two examples during TCM-92 and TCM-93 provide evidence that western North Pacific tropical cyclones may form and intensify in low latitudes, even when the adjacent upper-level flow would seem to be imposing a vertical wind shear exceeding the threshold value of Zehr (1992). In these two examples, the outflow from the developing tropical cyclone was locally opposing the impinging strong winds aloft in such a way that the tropical system remained vertically coherent. That is, the adjacent strong winds did not "shear off," or decouple, the upper-level outflow from the low-level circulation, which is observed to occur in many other tropical cloud clusters or incipient tropical disturbances.

In addition to the simple fact that these two tropical cyclones (Steve and Omar) were continuing to develop, evidence that the convective outflow was opposing and deflecting the impinging strong winds aloft was present in the high-resolution satellite imagery. In some cases, the leading edge of the convective outflow had a bow wave or convergent asymptote appearance as a sharp line of cirrus at the intersection with the
impinging winds. Animation of the imagery often indicates cloud elements that are being deflected parallel to the convergent asymptote and then around the incipient tropical disturbance. Smith (1994) found a diurnal variation in the position of the intersection between the outflow and the impinging winds. During the diurnal maximum of deep convection (roughly 1200–1800 UTC near Guam), the convective outflow appeared to push the intersection line upstream against the impinging flow. During diurnal minimum (roughly 0000–0600 UTC), the intersection line was right above the low-level circulation, which was revealed as curved bands of low-level cumulus in the visible imagery. Thus, it appears a key factor is the relative strength of the outflow from the convective cluster or incipient tropical cyclone by way of the impinging winds aloft.

These cases suggest a conceptual model of low-latitude vertical wind shear events involving TUTT cells, another tropical cyclone outflow, or the outflow from a monsoon depression. The hypothesis is that these systems tend to have only small vertical wind shear at low elevations, and the strong upper-level winds and vertical wind shear are concentrated in a shallow layer below the tropopause (Fig. 11a). Smith (1994) found the cirrus cloud-top temperatures over the pre-Steve disturbance had approximately the same values as over the adjacent TY Robyn. The impinging convective outflows from Steve and Robyn thus may have been concentrated in shallow layers at approximately the same elevation. The hypothesis is that apparent large vertical wind shear events associated with low-latitude circulations may actually be concentrated layers of upper-level winds that may be opposed or deflected by a strong, similarly concentrated outflow layer above a developing tropical cyclone. By contrast, the vertical wind shear associated with a midlatitude circulation may indeed be distributed somewhat linearly over depth as is presumed by calculating the shear as the 200-mb wind minus the 850-mb wind (Fig. 11b). Although not illustrated here, it is assumed that the con-
centrered outflow of a tropical cloud cluster or incipient tropical cyclone would not be as effective in opposing or deflecting an opposing wind shear distributed over a deep layer.

One of the objectives of this research has been to document that the operational analyses may not represent well the vertical shear in the region of a developing or intensifying tropical cyclone. In these two cases from TCM-92 and TCM-93, the meridional flow in the NOGAPS analysis passed over Steve and Omar, which led to vertical wind shears exceeding the Zehr (1992) threshold. As indicated above, satellite imagery reveals that the outflow above the developing/intensifying storms deflected the meridional flow around the storms. In almost all of these 200-mb analyses, cloud-drift winds were actually available in real time that properly depicted the outflows and deflections. Obviously these highly divergent winds were consistently rejected in the quality-control step because they departed too strongly from the 6-h model forecast that is used as the background field for the NOGAPS wind analysis.

Three aspects of the interactive MQI analysis ensure that the highly divergent winds are included. First, compositing the observations from 1800 to 0000 UTC and 0600 to 1200 UTC ensure that some real cloud-drift winds are available. In cases in which both times have these cloud-drift winds, the approximate doubling of the observations reinforces the reality of the divergent winds (more "buddy-checks"), so that it is clearer that such a departure from the background field is not an erroneous wind that should be rejected. Second, the sets of synthetic observations represent tropical cyclone outflows and point divergence from convective clusters are available for insertion, which ensures that the interactive analysis is consistent with the satellite image interpretation. Third, the MQI draws closely to the observations in a manner similar to a careful subjective analysis by an experienced analyst. By contrast, the operational analysis is a blend of the observations and the 6-h model forecast that minimizes root-mean-square errors in a global sense but may locally depart somewhat from observations.

It is recommended based on these two cases that FNOMC should test the impact of inclusion of synthetic observations above 400 mb to also represent the outflow layer of tropical cyclones. A proper outflow representation would likely improve retention of the adjacent winds in the quality control step. A second recommendation is that an interactive analysis of the type used here should be operationally tested. A "user-friendly" interactive analysis that composites observations over 6 h and has sets of synthetic observations for easy insertion, and machine-plots observations and analyses, would allow elimination of the hand plotting and subjective analysis presently done at JTWC. The forecaster/analyst must still study the satellite imagery and the observations to complete an accurate interactive analysis so that the ultimate objective of forming a complete synoptic interpretation would not be lost. A third recommendation would be to transmit interactive analysis gridpoint values from JTWC to FNOMC for inclusion in the postanalysis step that is a prelude to the next 6-h NOGAPS analysis. It seems likely that an improved representation at this step would result in retention of more of the highly divergent winds so that the next NOGAPS analysis (used as first-guess field) would require less modification in the subsequent interactive analysis. It follows that a better analysis should improve both track and intensity forecasts of tropical cyclones.

Based on these preliminary analyses and interpretations, forecasters should perhaps distinguish between large vertical wind shear events involving midlatitude circulations (Fig. 11b) versus low-latitude circulations.

Fig. 10. Vertical wind shear (m s\(^{-1}\), left ordinate) between 200 and 850 mb for NOGAPS (dash-dot), final MQI analyses (dashed), and the threshold value of Zehr (horizontal solid). Maximum intensity (1 kt \(\approx 0.5\) m s\(^{-1}\), right ordinate) of Omar (heavy solid) during 2100 UTC 23 August–0900 UTC 27 August 1992.

Fig. 11. Schematics of the 200–850-mb wind shear arising from (a) a low-latitude system with upper-tropospheric winds concentrated in a shallow layer versus (b) linearly distributed over a deep layer as might exist in a midlatitude trough.
in which the strong winds may be concentrated in shallow layers (Fig. 11a). In either case, the problem of forecasting the impact of adjacent systems on the formation and intensification of tropical cyclones is difficult because of the highly transient interaction of two (or more) translating and developing circulations. Clearly, forecasting the juxtaposition of such systems is a nonlinear problem that may have a lower predictability. Nevertheless, a conceptual model of low-latitude vertical wind shear events may assist the forecaster/analyst to resolve apparently conflicting views from satellite imagery, aircraft reports, and large-scale analyses in cases of tropical cyclone formation and intensification at low latitudes.

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