Reply

GREG J. HOLLAND

Bureau of Meteorology Research Centre, Melbourne, Australia

YUQING WANG

Centre for Dynamical Meteorology and Oceanography, Monash University, Melbourne, Australia

MARK LANDER

University of Guam, Mangilao, Guam

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We are pleased to see that Holland and Lander (1993, hereafter HL) has stimulated the interest of Khandekar. As indicated in the paper, this was the first of a series of studies aimed at investigating the mechanisms responsible for the observed meandering motion of tropical cyclones. We focused on the tendency for tropical cyclones to meander about a longer-term track with periods of several days and amplitudes around 100 km. Our conclusions were that the Yeh (1950) and Kuo (1969) aerodynamic interaction mechanisms and the Syono (1955) and Futi (1956a,b) inertial oscillation explanations could not be universally applied to the observed meanders. We noted several potential mechanisms leading to the meandering motion of a tropical cyclone. A detailed case study of large-amplitude meanders arising from interactions between a developing tropical cyclone and a nearby mesoscale convective system was presented.

Khandekar refers to Khandekar and Rao (1975) to suggest that the vertical structure of a vortex can have an important role in determining the oscillatory movement of tropical cyclones. Detailed information on the current level of knowledge of baroclinic vortex interaction may be found in Hopfinger and van Heijst (1993) and Wang and Holland (1994). We agree that some oscillations can arise from vortex tilting and have provided examples in HL. However, the methodology adopted by Khandekar and Rao significantly overstates the degree of interaction. They use a two-layer model in which the interface is free, thus producing a direct pressure gradient in the lower level from the upper-level vortex. The point vortices that are used also have significantly stronger outer circulations than is normally encountered (Holland 1980). Vortices in a baroclinic environment may oscillate in the manner described by Khandekar, but many systems adopt a stable tilted structure without any oscillation occurring (Wang et al. 1993). Fully developed tropical cyclones also have very little vertical tilt, so that any oscillations could normally be expected to be less than the radius of maximum winds and may be small compared to the effects of nearby convective asymmetries, as described in HL and Willoughby (1988). Further, a tropical cyclone interaction with a large-scale synoptic system, such as the monsoon trough, can produce both large- and small-scale meanders in the cyclone track (Ritchie and Holland 1993; Carr 1993), and tropical cyclones may induce changes in their environment that lead to track meanders (Holland and Dietachmayer 1993).

The comment by Khandekar confusingly jumps between vertical interaction processes and unsubstantiated support for the barotropic theories of Yeh and Kuo, which we do not support (see HL for substantiation). It is interesting that Khandekar invokes the barotropic Kuo mechanism to explain the oscillatory motion of tornadoes, which normally have considerable vertical tilt. We disagree with Khandekar's claim that all scales of tropical cyclone meander (including synoptic) can be explained by self-interaction of a tilted vortex, especially the unsubstantiated claims that binary cyclone interaction can be simulated in this manner. Wang and Holland (1994) have shown that vortex tilt can increase the degree of mutual attraction of tropical cyclones, but such interaction is highly complex and subject to many other processes. Finally, Khandekar's Fig. 1 is incorrect. The lower vortex is misplaced (unless it is anticyclonic), and the system is made up of two discrete vortices, not a sloping vortex as indicated.

Corresponding author address: Dr. Greg Holland, Bureau of Meteorology Research Centre, GOP Box 1289K, Melbourne, Victoria 3001, Australia.

The meandering nature of tropical cyclones is a substantial forecast problem, as difficulties arise in determining meanders from actual track changes. The mechanisms also apply to a wide range of fluids and scales and are of considerable scientific interest. We hope that this exchange will stimulate Khandekar to make further contributions to the current level of understanding.

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