14B.1 CONCEPTUAL MODEL OF WESTERN NORTH PACIFIC MONSOON DEPRESSION FORMATION

J. C. Beattie[1] and R. L. Elsberry[2]
[1] U. S. Naval Academy, Annapolis, MD; [2] Naval Postgraduate School, Monterey, CA

1. INTRODUCTION

As used at the Joint Typhoon Warning Center (JTWC), the definition of a monsoon depression is a large cyclonic vortex with a diameter on the order of 1000 km that contains a loosely organized cluster of deep convection and has a light wind core surrounded by a band of stronger winds at large radii. Monsoon depressions are one synoptic-scale feature favorable to tropical cyclone formation over the western North Pacific during the summer monsoon. Little is known about the processes that influence the formation and development of the monsoon depression.

A conceptual model of formation has been developed based on the formations of two monsoon depressions that occurred within 3 days in early July 2007 in the western North Pacific. The first monsoon depression was a long-lasting feature that did not transition to a tropical cyclone. The second, larger monsoon depression was short-lived as it transitioned into Typhoon Man-Yi. These two monsoon depressions became the basis for a monsoon depression formation conceptual model.

Based on the initial observations of the formation of the pre-Typhoon Man-Yi monsoon depression, three possible mechanisms were hypothesized to contribute to its formation. The first mechanism was cross-equatorial flow, the second was approach of an easterly wave to the eastern end of the monsoon trough, and the third was Rossby wave dispersion from a South China Sea tropical cyclone to the first monsoon depression upstream of the developing (larger) pre-Typhoon Man-Yi monsoon depression. Assessment of the relative contributions to formation via each hypothesized mechanism was by means of a wave activity flux study, specifically whether a wave activity flux convergence was occurring in the appropriate region, and if that convergence was associated with a spin-up of cyclonic vorticity associated with monsoon depression formation. The mechanism found to play a primary role in the formation of the two monsoon depressions was the cross-equatorial flow from the Southern (winter) Hemisphere. This mechanism has also been found to contribute to the formation of the pre-Typhoon Robyn (early August 1993) monsoon depression and in several formations during the period from September through October 2009.

**Corresponding author address:* Jodi Beattie, U. S. Naval Academy, Dept of Oceanography, Annapolis, MD 21402; e-mail: beattie@usna.edu.

2. CROSS-EQUATORIAL FLOW

This primary mechanism for monsoon depression formation is somewhat similar to the influence of the winter hemisphere proposed by Love (1985a and b). Love (1985a and b) demonstrated winter hemisphere events could influence tropical cyclone formation in the summer hemisphere equatorial trough (monsoon trough). Love (1985b) also links cross-equatorial flows and tropical cyclone formation in the summer hemisphere via enhanced easterlies that arise due to the summer hemisphere subtropical high being forced eastward by the enhanced westerlies. Love (1985b) also discusses the large-scale transition from equatorial trough (monsoon trough) to tropical cyclone via a pre-genesis cluster. Love (1985b) provides enough detail in the description to conclude that his pre-genesis cluster is representative of what the JTWC now defines as a monsoon depression.

In the July 2007 case, a cross-equatorial flow (now also referred to as a southerly surge) penetrates into the summer hemisphere and enhances the equatorial westerlies. As will be described, the southerly surge in the pre-Typhoon Man-Yi monsoon depression case enhanced the horizontal shear and curvature vorticity of the region by enhancing the equatorial westerlies and turning the southern-most end of the monsoon trough northward to form a cyclonic vorticity lobe. This lobe later combined with a weaker lobe of cyclonic vorticity that already existed in the monsoon trough to form the monsoon depression.

Analysis of the two monsoon depression formations before the formation of Typhoon Man-Yi (TY 04W) indicates a southerly surge occurred in both the western and eastern regions of the analysis domain (Fig. 1). The western cross-equatorial flow crossed Malaysia in the region west of New Guinea. The eastern cross-equatorial flow originated east of New Guinea.

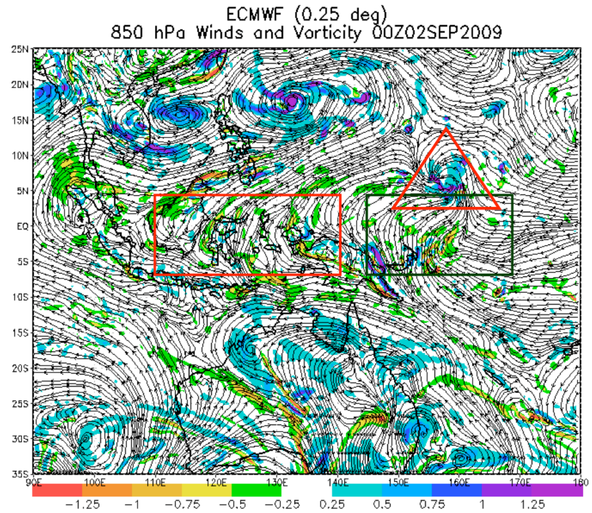

Figure 1: 850 hPa Winds and Vorticity (0000UTC02SEP2009); Red box depicts the western domain; Green box depicts the eastern domain. Red triangle shows a developing monsoon depression.

3. CONCEPTUAL MODELS

3.1 *Southerly Surge Air Streams*

A conceptual model of the cross-equatorial flow based on the pre-Typhoon Man-Yi study considers three paths. The first air stream (labeled A in Fig. 2a) is the western portion of the southerly surge. As illustrated in Fig. 2b, this air stream originates in the Southern Hemisphere anticyclone, turns to the left, and becomes an easterly wind to the south of the Equator. This stream then crosses the Equator in the western domain (Fig. 1) and becomes westerlies under the Coriolis effect (Fig. 2b). The second air stream (labeled B in Fig. 2a) is in the central portion of the southerly surge. This air stream has enough momentum to penetrate far into the Northern Hemisphere and then the Coriolis effect turns the flow to the right (Fig. 2c). This air stream becomes a southwesterly wind that enhances the equatorial westerlies and interacts with an established monsoon trough to change the horizontal shear vorticity of the monsoon trough (or a confluent region) into curvature vorticity (dashed portion of Fig. 2c). Given the proper superposition with the confluent region at the end of the monsoon trough, the southerly surge flow is wrapped it into a cyclonic circulation. In the pre-Typhoon Man-Yi case, the southerly surge flow becomes the western lobe of two cyclonic lobes that later combine to become the monsoon depression. A similar evolution of air stream B was observed in the formation of the earlier monsoon depression to the east of the Philippines.

Air stream B was not the only air stream involved in the pre-Typhoon Man-Yi case. The third air stream (labeled C in Fig. 2a) is the eastern portion of the surge and has sufficient velocity to cross the equator. After this air stream is turned to the right by the Coriolis effect, it converges with the stronger trade easterlies and is deflected back into the Southern Hemisphere. This new northerly flow and the southerly flow to the west create, or enhance, a clockwise circulation just south of the Equator. The western side of this clockwise circulation then creates a second southerly surge that penetrates farther north into the summer hemisphere (dashed portion Fig. 2d), which then interacts with the monsoon trough.

In the pre-Typhoon Man-Yi monsoon depression formation, a cyclonic circulation was present in the Southern Hemisphere just to the south of where the pre-Typhoon Man-Yi monsoon depression formed. This cyclone was a result of a southerly surge in the eastern domain that evolved similar to air stream C. In this case, air streams B and C (second surge of stream C; Figs. 2a and d) enhanced the eastern end of the monsoon trough and created the eastern lobe of the developing monsoon depression. Continued southerly surge, and therefore enhanced southwesterlies, for a period of time led to increased vorticity in the monsoon depression.

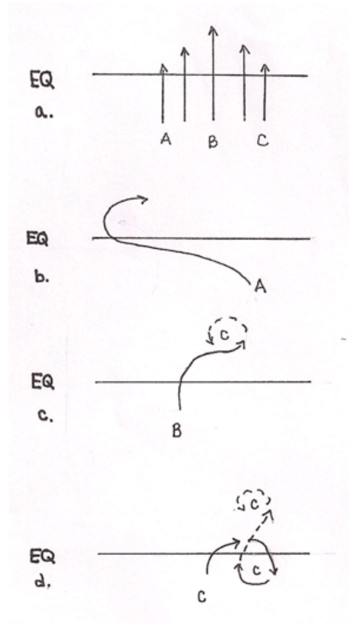

Figure 2: Conceptual diagrams of three regions (A, B, and C) in a cross-equatorial flow stream during a southerly surge.

Examination of a number of cases indicates that the cross-equatorial stream that dominates is dependent on the locations of the Southern Hemisphere midlatitude cyclones and anticyclones. For example, the cross-equatorial flow may come from the eastern side of the anticyclone. While this anticyclone is to the west of and over Australia, streams A and B develop (Figs. 3 and 4). If a cyclone is to the southeast of the anticyclone, or if the anticyclone is farther to the east, then the outflow is larger and cross-equatorial flow in the eastern portion of the domain can be initiated (Fig. 1). Another scenario is that the cross-equatorial flow in the eastern domain is from Southern Hemisphere easterlies that have converged with the outflow from the subtropical anticyclone and were deflected northward, as can be observed in the southeastern portion of Fig. 1.

3.2 *Monsoon Depression Formation*

The cross-equatorial flow establishes a confluent region between the equatorial westerlies and trade easterlies as it enhances the equatorial westerlies. In the first monsoon depression formation, this confluent region was an east-west oriented monsoon trough (MT_1 in Fig. 3). In the second monsoon depression formation, it was a traditional northwest-southeast oriented monsoon trough (MT_2 in Fig. 4). As described in the study by Kuo et. al. (2001), it is not sufficient to have a region of confluence to yield a cyclonic circulation, as convergence is actually needed. In this conceptual model of monsoon depression formation, it is the southerly surge that provides this convergence as observed in the wind and vorticity fields, and its critical role will be documented later via wave activity flux calculations.

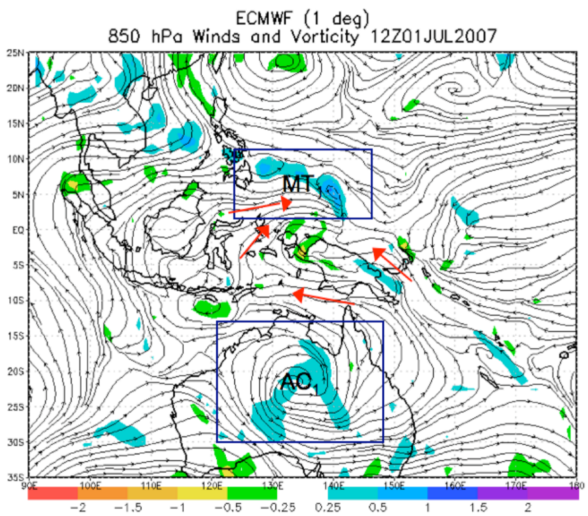

Figure 3: 850 hPa Winds and Vorticity (1200UTC01JUL2007); MT_1 box depicts the east-west oriented monsoon trough that lead to the first, long-lasting monsoon depression east of the Philippines. Two streams (as in A and B in Figs. 2b and c) of cross-equatorial flow that are related to the location and movement of the Southern Hemisphere anticyclone (AC_1) are highlighted by the red arrows.

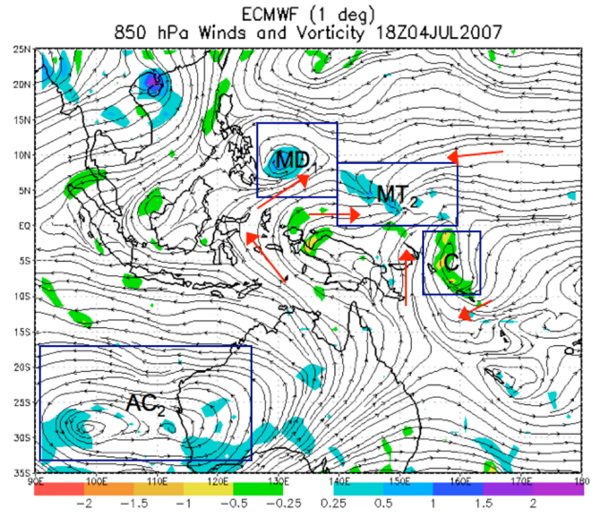

Figure 4: 850 hPa Winds and Vorticity (1800UTC04JUL2007); Following the formation of the first monsoon depression MD_1, a second monsoon depression forms in association with the traditionally oriented monsoon trough, MT_2. A near-equatorial cyclone (C) in the Southern Hemisphere also facilitates cross-equatorial flow (red arrows). A second Southern Hemisphere anticyclone (AC_2) in conjunction with the midlatitude westerly trough contributes to sustained cross-equatorial flow (red arrows).

In this conceptual model, the formation of monsoon depressions in the western North Pacific begins with cross-equatorial flow enhancing the equatorial westerlies. This enhanced westerly flow contributes to a confluent region between the equatorial westerlies and trade easterlies, which may also be a monsoon trough. A second southerly flow into the confluent region acts to wrap up the eastern, or southeastern depending upon the orientation, end of the confluent region and thus provides another lobe of maximum cyclonic vorticity. This new lobe merges with an existing lobe of cyclonic vorticity along the confluent region and the flow becomes more cyclonic. Convection in the confluent region associated with the trade easterlies and equatorial westerlies, as well as new convection in association with the eastern cyclonic vorticity lobe, along with the maximum winds around the periphery of this new large cyclonic region then fits the JTWC definition of a monsoon depression.

4. OBSERVATIONAL STUDY

The general applicability of this conceptual model of monsoon depression formation was examined utilizing high-resolution ECMWF analyses (0.25 degree from the Year of Tropical Convection (YOTC) data set) from 1 September through 31 October 2009. Of the 12 monsoon depressions observed during this period, five transitioned to tropical cyclones, which provides motivation to study the formation of monsoon depressions as potential favorable regions for tropical cyclone formation. Thus, the conceptual model developed from the pre-Typhoons Man-Yi and Robyn could be extended to these formations as well.

One example from the 2009 period was the pre-Typhoon Parma monsoon depression, which also formed in the same sequence of cross-equatorial flows as in the conceptual model (Fig. 5). In the later stages of this formation, the Southern Hemisphere anticyclone is providing cross-equatorial flow primarily in the western region. The eastern region flow is a combination of flow from the Southern Hemisphere subtropical anticyclone and from the Southern Hemisphere easterlies. The confluent region associated with the eastern flow has already wrapped into cyclonic flow, as suggested by the conceptual model (demonstrated in the red triangle in Fig. 1).

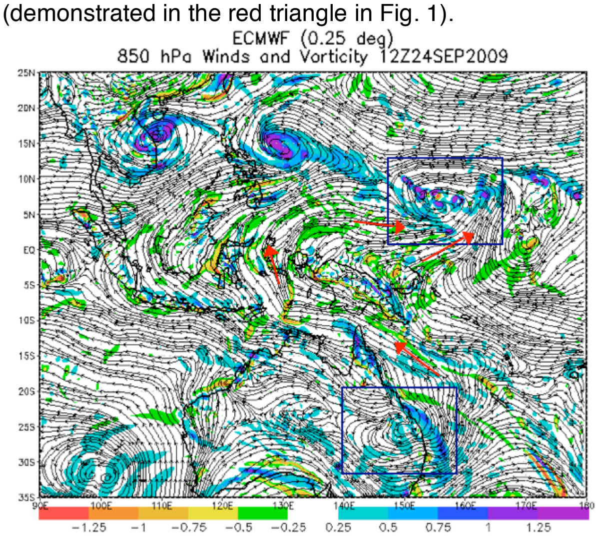

Figure 5: 850 hPa Winds and Vorticity (1200UTC24SEP2009); Southern Hemisphere box highlights the anticyclone, while the Northern Hemisphere box highlights the developing monsoon depression.

5. CONCLUSION

The observational study of 12 monsoon depressions from 2009 confirmed the initial observations and the components of the conceptual model in that the combination of a confluent region (or monsoon trough) and a southerly surge are the necessary ingredients for monsoon depression formation. This qualitative analysis of the high-resolution data will be further investigated by means of the wave activity flux study similar to that performed on the initial pre-Typhoon Man-Yi data set. The angular momentum transport study of Love (1985b) is analogous to the wave activity flux study being carried out on the pre-Typhoon Man-Yi monsoon depression, which suggests the study will be beneficial for investigating other monsoon depression formations.

6. ACKNOWLEDGMENTS

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