Western North Pacific Monsoon Depression Formation

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ABSTRACT

Relatively few studies have been carried out as to the conditions leading to the formation of monsoon depressions in the western North Pacific. Two monsoon depression formations during July 2007 were analyzed using ECMWF analyses and satellite observations. Wave-activity flux calculations indicated that cross-equatorial flow from the Southern Hemisphere played an important role in the formation of these monsoon depressions. A new conceptual model of monsoon depression formation in the western North Pacific is proposed that includes three southerly airstreams in the Southern Hemisphere that lead to cross-equatorial flows into the Northern Hemisphere. Examination of 44 monsoon depressions from April to December 2009 confirms the critical role of these cross-equatorial flows in monsoon depression formation. All of the monsoon depressions in the 2009 sample for which formation conditions could be established had at least one of three possible airstreams that interacted with a confluent region and, thus, may be a necessary condition for monsoon depression formation. This conceptual model of monsoon depression formation was further confirmed by means of wave-activity flux calculations and backward trajectory ensembles for the 2009 cases.

1. Introduction

The monsoon depression is one of the synoptic-scale circulations that are favorable for tropical cyclone formation over the western North Pacific; indeed, Lander (2004) suggests that almost two-thirds of these monsoon depressions transition to tropical cyclones. Therefore, a better understanding of the formation of the monsoon depression is expected to improve the forecast skill in identifying the regions of deep convection that would most likely lead to the formation of a tropical cyclone, and decrease the false alarm rate as only a small number of the convective clusters actually become tropical cyclones. The Joint Typhoon Warning Center (JTWC 1994) defines a monsoon depression as a large cyclonic vortex with a diameter on the order of 1000 km that contains a loosely organized cluster of deep convection around the periphery and has a light wind core surrounded by a band of stronger winds at larger radii.

Little is known about the processes that influence the formation, structure, and development of the monsoon depression in the western North Pacific. The primary objective of this research is to develop a new conceptual model of monsoon depression formation in the western North Pacific based on high-resolution European Centre for Medium-Range Weather Forecasts (ECMWF) analyses and various satellite observations. The second objective is to examine the possible physical mechanisms of formation based on the new conceptual model.

A comprehensive conceptual model and working definition of monsoon depression formation should assist forecasters in identifying deep convective regions that will first lead to monsoon depression formation and possibly to tropical cyclone formation. The long-range goal is to contribute to a better understanding of monsoon depression formation and structure to lead to future improvements in numerical modeling so that more accurate identifications of suspect deep convection regions can be achieved.

In section 2, a synoptic analysis of the formations of two monsoon depressions in the western North Pacific that occurred within 3 days in early July 2007 is discussed. In section 3, some possible physical mechanisms for monsoon depression formation will be explored based on the July 2007 case. A new conceptual model of monsoon depression formation will be proposed in section 4. This new conceptual model is an extension of the Harr and Elsberry (1996) description of the pre–Typhoon Robyn (1993) monsoon depression. In section 5, the applicability of the conceptual model is examined through
an observational study of 44 cases during April–December 2009 using satellite imagery and analyses. A summary and some conclusions will be presented in section 6.

2. Synoptic analysis of the July 2007 monsoon depression formations

The monsoon depression that transitioned into Typhoon Robyn during early August 1993 was the initial prototype of monsoon depression formation for this study. As analyzed by Harr and Elsberry (1996), the formation of the pre–Typhoon Robyn monsoon depression occurred due to the confluence of trade easterlies and equatorial westerlies. As the cloud bands with embedded mesoscale convective systems in the easterlies and westerlies began to wrap around a region of lower pressure, the associated regions of higher winds resulted in a large, cyclonic circulation. In combination with the convection on the periphery, this circulation fit the definition of a monsoon depression (JTWC 1994; Lander 2004).

Two monsoon depressions from July 2007 that formed within 3 days in early July 2007 in the western North Pacific (Fig. 1) became the basis of the new conceptual model of monsoon depression formation. The first monsoon depression formed at 7°N in the northwest portion of the domain near the Philippines, and was a long-lasting feature that did not transition to a tropical cyclone. The second, larger monsoon depression closer to the equator (4°N) was short lived, less than 3 days, as it transitioned into a tropical cyclone (Typhoon Man-Yi).

a. Monsoon depression MD1

An east–west-oriented monsoon trough, MT1, anchored east of the southern Philippines near 9°N, 125°E had become established by 1 July (Fig. 2) and would on 3 July become the source region for monsoon depression MD1 (Fig. 3). Cross-equatorial flow in the western
portion of the domain (from over Malaysia and western New Guinea; 115°–135°E) increased, and due to the Coriolis effect the flow became westerlies that established the southern portion of the monsoon trough MT1 (Fig. 2). A cyclonic vorticity lobe then developed along the confluent region at the western end of the monsoon trough. Although the cross-equatorial flow diminished after this time, it strengthened again at 1200 UTC 2 July (not shown) and further enhanced the Northern Hemisphere westerly flow. As the enhanced equatorial westerlies became more southerly and approached the eastern end of the established east–west monsoon trough MT1, along 5°N, they resulted in the development of a separate eastern lobe of cyclonic vorticity. By 0000 UTC 3 July, the eastern vorticity lobe combined with the preexisting vorticity lobe and resulted in a large cyclonic circulation (not shown). This circulation, which was near 7°N, 131°E at 1200 UTC 3 July (Fig. 3; MD1), developed from the cross-equatorial flow and fit all characteristics of a monsoon depression as defined by Lander (1994, 2004) and the JTWC (1994).

b. Monsoon depression MD2

By 1200 UTC 3 July (Fig. 3), a chain of cyclonic circulations extended southeastward from Typhoon Toraji that had formed in the South China Sea. Monsoon depression MD1 was the second cyclonic circulation in the chain, and was followed by a southeast-to-northwest-oriented monsoon trough (labeled MT2 in Fig. 3) that formed on 3 July to the southeast of MD1. This monsoon trough (MT2) was well established by 1800 UTC 4 July with a maximum vorticity lobe at 850 hPa near 4°N, 150°E. The formation of this second monsoon trough occurred as Typhoon Toraji continued to move toward the northwest and monsoon depression MD1 moved slowly westward. During this period, persistent cross-equatorial flow had turned clockwise to form westerlies equatorward of both monsoon troughs, and persistent trade wind easterly flow existed throughout the eastern portion of the domain. A branch of cross-equatorial flow in the central domain (125°–135°E) contributed to the enhancement of the westerlies flowing into the monsoon trough MT2. These enhanced equatorial westerlies formed a confluent region with the trade easterlies that then contributed to enhanced regions of cyclonic vorticity along the monsoon trough. As described by Kuo et al. (2001), it is not enough to have a region of confluence to yield a cyclonic circulation, convergence is also needed. In these monsoon depression formations, it is hypothesized that the cross-equatorial flow leads to enhanced
westerlies and convergence with the trade easterlies in
the confluent region of the monsoon trough.

A separate branch of cross-equatorial flow in the
eastern domain (east of New Guinea; 145°E–160°E) was
part of a near-equatorial cyclonic circulation in the
Southern Hemisphere (labeled CSH in Fig. 3) near 5°S,
158°E. By 1800 UTC 5 July (Fig. 4), this eastern cross-
equatorial flow had penetrated far enough northward
to combine with the trade easterlies, which created a region
of convergence within the eastern end of the monsoon
trough and formed an eastern lobe of cyclonic vorticity.
Early stages of this sequence can be observed in Fig. 3. In
addition to the typical cloudiness in the warm and moist
equatorial westerlies in the southwest quadrant of the
cyclonic vorticity lobe, the convergent region on the
southeastern end of the circulation resulted in a cloud
band wrapping around the eastern side of the monsoon
trough (Fig. 4). The associated precipitation band and
850-hPa winds on the southeastern and eastern end of
the monsoon trough contributed to a broad elliptical
circulation with a west-southwest to east-northeast ori-
entation that fulfilled the criteria for a monsoon depres-
sion (Lander 2004; JTWC 1994).

As in monsoon depression MD1, the combination of
the two cyclonic vorticity lobes at the eastern and western
ends of the monsoon trough formed a large cyclonic cir-
culation with outer wind maxima that were well aligned
with TRMM precipitation. The merger of these vorticity
lobes resulted in the formation of a monsoon depression
(MD2). Once the monsoon depression formed, the cross-
equatorial flow continued in response to lower pressure in
the depression.

In summary, cross-equatorial flows in the western and
central regions of the domain enhanced the equatorial
westerlies flowing into the monsoon trough, which are
hypothesized to increase the horizontal shear and cur-
vature vorticity in the region. Another cross-equatorial
flow in the eastern portion of the domain interacted with
the southeastern end of the monsoon trough to form
a cyclonic vorticity lobe that then began to wrap the
monsoon trough into a cyclonic circulation. Each of
these cross-equatorial flows was accompanied by re-
regions of deep convection and cirrus-level outflows that
then wrapped around an inner region of minimal deep
convection, as observed in Fig. 1. Because the deep
convection tended to be concentrated in the confluent

FIG. 3. Streamlines and relative vorticity as in Fig. 2, but at 1800 UTC 4 Jul 2007 and including
a chain of cyclonic circulations that extend southeastward from Typhoon Toraji in the South
China Sea. Following the formation of the first monsoon depression MD1, a second monsoon
depression will form in association with the traditionally oriented monsoon trough MT2. A
Southern Hemisphere anticyclone (AC) in conjunction with the midlatitude westerly trough
contributes to sustained cross-equatorial flow. A near-equatorial cyclone (CSH) in the Southern
Hemisphere also facilitates cross-equatorial flow.

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regions between the trade easterlies and equatorial westerlies, convection during the monsoon depression formation stage was associated with the eastern and western cyclonic vorticity lobes. Furthermore, the maximum winds were found along the circulation periphery, which was of order 1000 km in diameter and had a cloud- and precipitation-free center.

3. Physical mechanisms

Based on the analyses of the two July 2007 monsoon depression formations, three physical mechanisms are examined that may have contributed to their formation. The first is Rossby wave dispersion along a chain of cyclonic circulations, as in Fig. 3; the second is energy flux associated with easterly waves; and the third is energy flux associated with a cross-equatorial (southerly) flow. Each mechanism was investigated by means of a wave-activity flux calculation to determine the primary mechanism for formation. Takaya and Nakamura (2001) used the wave-activity flux to identify wave propagation and understand the atmospheric dynamics of stationary and propagating small-scale anomalies.

a. Rossby wave dispersion

Rossby wave dispersion was considered as a possible contributor to the monsoon depression formation following several wave-activity flux convergence studies (e.g., Sobel and Bretherton 1999; Molinari et al. 2007) in which disturbance formation occurred to the southeast of an already mature cyclonic system. As indicated in Fig. 3, Typhoon Toraji was located in the South China Sea to the northwest of monsoon depression MD1 that formed to the east of the Philippines. Both circulations were to the northwest of the MT2 region where the second monsoon depression would form. Thus, one interpretation from this analysis was that a wave train from Typhoon Toraji to monsoon depression MD1 would continue to create a wave-activity flux from the northwest that would contribute to the developing monsoon trough MT2 (Fig. 3) and eventually lead to the formation of the second monsoon depression MD2.

The hypothesis is then that a cascade of wave-activity flux to the southeast of each feature would result in an increase in cyclonic vorticity in the regions of each developing monsoon depression. The wave-activity flux was calculated using streamfunctions ($\Psi$) derived from the ECMWF 1° analysis of zonal ($u$) and meridional ($v$) wind components at 850 hPa. Following the Takaya and Nakamura (1997, 2001) studies, the zonal ($x$) and meridional ($y$) components of the wave-activity flux are

$$WF_x = \frac{1}{2} \left( \frac{u_b (v^2 - \psi \frac{\partial u}{\partial x}) + v_b (\psi \frac{\partial u}{\partial x} - uv)}{|u|} \right),$$

and

$$WF_y = \frac{1}{2} \left( \frac{u_b (\psi \frac{\partial u}{\partial x} - uv) + v_b (u^2 - \psi \frac{\partial u}{\partial y})}{|u|} \right).$$
where $|U| = \sqrt{u_v^2 + v_v^2}$ and $u_v$ and $v_v$ are the mean zonal and meridional wind components, respectively, at 850 hPa. Although these wave-activity fluxes (m$^2$ s$^{-2}$) were calculated globally, they have been rescaled for display in the region of interest (35°S–25°N, 90°E–180°). A running 1-day mean of the 6-h wave-activity fluxes was performed to eliminate some small-scale variability.

Wave-activity fluxes for the domain are shown in Figs. 5a–d from 0600 UTC 4 July to 0600 UTC 6 July. Note that the regions of maximum wave-activity flux (vectors) divergence (shaded) coincide with the cyclonic systems, as depicted in Fig. 3. If Rossby wave dispersion was contributing to the monsoon depression formations during this period, the expectation would be that the wave-activity flux vectors point toward the southeast. Whereas wave-activity flux emanating from Typhoon Toraji (Fig. 5a) was toward the southeast into the trailing anticyclone, the flux from the trailing anticyclone was small and did not reach the region where monsoon depression formed (not shown). The flux vectors from the trailing anticyclone remained small and did not have a preferred direction through the time period shown.

Wave-activity flux also emanated from monsoon depression MD1 (Figs. 5a–d), but did not extend to the region where the second monsoon depression would form (labeled MT2 in Figs. 5a and 5b), as the flux vectors were also pointing southward. Therefore, this mechanism was not considered to be a contributing factor to monsoon depression formation as Typhoon Toraji, monsoon depression MD1, and monsoon depression MD2 evolved independently without a direct connection via the wave-activity flux convergence to the subsequent cyclonic circulations in the apparent wave train (Figs. 3 and 5a–d).

b. Waves in the easterlies

Various researchers (e.g., Briegel and Frank 1997; Ritchie and Holland 1999; Sobel and Bretherton 1999; Kuo et al. 2001; Frank and Roundy 2006) have concluded that wave growth in a convergent background flow with positive vorticity provides an environment favorable for tropical cyclone formation. Dickinson and Molinari (2002) documented easterly waves that transitioned to tropical disturbances from which tropical cyclones later would form. Thus, a second hypothesis (as similarly proposed by Molinari et al. 2007) is that monsoon depression formation is due to the interaction of a wave in the easterlies with the eastern end of a monsoon trough. Molinari et al. (2007) also emphasized the importance of horizontal variations in the background flow and therefore their role in contributing to synoptic-scale disturbance growth.

The hypothesized physical mechanism is that a wave in the easterly flow is dispersive so the associated wave-activity flux would contribute to monsoon depression formation as it approaches the formation region from the east. No evidence was found that a wave in the easterlies approached the formation region of monsoon depression MD1 (not shown). A wave in the easterlies (Fig. 4, small box) did approach the formation region of monsoon depression MD2 before formation. However, the wave-activity flux vectors in Figs. 5a and 5b in the region of the wave in the easterlies are not directed toward the region where the monsoon depression formed (i.e., monsoon trough MT2). It was only after MD2 formed that a connection in the wave-activity flux existed between the wave and the northeastern quadrant of the monsoon depression (Figs. 5c and 5d). Even though this mechanism was not considered to be significant for this case of monsoon depression formation, the wave in the easterlies may have contributed to the transition of this monsoon depression to a tropical cyclone. Assessment of such a contribution will be a future topic of research.

c. Cross-equatorial flow

The synoptic analysis in section 2 suggests a connection between the cross-equatorial flow from the Southern (winter) Hemisphere that provides enhanced westerly flow into a confluent region between the trade easterlies and equatorial westerlies. In addition, southerly flow into the eastern end of the monsoon trough appeared to increase the horizontal shear and cyclonic vorticity in the region of monsoon depression formation.

Love (1985a) demonstrated that winter hemisphere events could influence tropical cyclone formation in the summer hemisphere equatorial trough (monsoon trough). Love (1985a) suggested that the onset of cross-equatorial flow would be initiated when a rise in subtropical pressure propagated equatorward. If an associated cold surge in the lower troposphere raised the pressure along the equator west of the genesis region, a west-to-east pressure gradient would lead to enhanced monsoon westerlies from the surface to 500 hPa (Love 1985a). Love (1985b) also discussed the large-scale transition from equatorial trough (monsoon trough) to tropical cyclone via a pregenesis cluster. Love (1985b) provides enough information to conclude that the pregenesis cluster has similar characteristics to what Lander (2004) and the JTWC (1994) define as a monsoon depression.

Southerly wave-activity flux vectors also occurred in the same location as the cross-equatorial airstreams originating from the Southern Hemisphere prior to both monsoon depression formations (Fig. 5). These northward-pointing flux vectors were particularly well-defined moving into the region of the second monsoon
FIG. 5. Wave-activity flux vectors (m$^2$ s$^{-1}$), 1-day running mean of the streamfunction anomaly (contours), cyclonic vorticity regions (shading magnitudes are in the same range as previous figures) with vorticity maxima at 850 hPa that are labeled corresponding to the cyclonic circulations for (a) 0600 UTC 4 Jul, (b) 0000 UTC 5 Jul, (c) 1800 UTC 5 Jul, and (d) 0600 UTC 6 Jul 2007.
depression formation (Figs. 5a and 5b). Note especially the wave-activity flux vectors associated with the Southern Hemisphere cyclone, C_{SH}, in Figs. 5a–d that then resulted in flux convergence in the region of the MD2 formation. Thus, these wave-activity flux vectors are consistent with the hypothesis that a primary physical mechanism for monsoon depression formation in the western North Pacific is cross-equatorial flow from the Southern Hemisphere.

4. Conceptual model

Based on the synoptic analysis and wave-activity fluxes for the two July 2007 monsoon depressions, a new conceptual model of monsoon depression formation in the western North Pacific is proposed that involves three types of cross-equatorial flows (Fig. 6) that tend to be in the western (airstream A), central (airstream B), and eastern (airstream C) regions of the domain. Each of these airstreams may interact with the Northern Hemisphere trade easterlies in a confluent environment to create the broad cyclonic circulation of a monsoon depression. It is these cross-equatorial flows that distinguish the new conceptual model from that of Harr and Elsberry (1996), who only considered the Northern Hemisphere aspects. The hypothesis that these cross-equatorial flows are a primary mechanism for monsoon depression formation is somewhat similar to the influence of the winter hemisphere proposed by Love (1985a,b), as discussed in section 3c.

Although their focus was on convective clusters developing in the Southern Hemisphere (15°S–0°, 85°–100°E), Fukutomi and Yasunari (2005) documented southerly surges during June–August that penetrated to the equator and interacted with the Northern Hemisphere equatorial westerlies. They defined a surge index based on the 850-hPa meridional winds for a specific box in the eastern South Indian Ocean. Composites (their Fig. 3) of the 850-hPa winds during 63 strong southerly surge events that occurred between 1979 and 2001 resemble the evolution in Fig. 4 leading to the formation of monsoon depression MD2. Even though Fukutomi and Yasunari (2005) define these southerly surges as “sub-monthly,” their case studies indicate a time scale of about 4 days, and they associate the southerly surge with an amplifying midlatitude wave train.

Large-scale circulations such as the Southern Hemisphere cross-equatorial flows, trade easterlies, and equatorial westerlies that establish the monsoon trough in the Northern Hemisphere may be somewhat quasistationary on the time scales leading up to a monsoon depression formation. However, the eastward-translating anticyclonic cells that trail the midlatitude troughs in the Southern Hemisphere that are proposed to contribute to

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1 Reference provided by anonymous reviewer.
the monsoon depression formations are more transient and dictate that trajectories would be more illustrative than streamlines. Therefore, backward trajectories from the monsoon depression formation locations were calculated using the Air Resources Laboratory’s (ARL) Hybrid Single Particles Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Rolph 2011). Analyses from the National Centers for Environmental Prediction (NCEP) Global Data Assimilation System (GDAS) were the input for the HYSPLIT model.

Using the ARL HYSPLIT web interface, 120-h backward trajectories were plotted for both July 2007 monsoon depression formations. To trace the trajectories to a Southern Hemisphere midlatitude source region, a compilation of 120-h analyses was examined (Figs. 7 and 8). The first backward-trajectory ensemble originates at the edge of the monsoon depression (star), and the second originates from a point (star) within the first set of trajectories that crossed the equator, which then shows where the trajectories originate in the Southern Hemisphere. As did the wave-activity flux calculations, these backward trajectories show that flow begins in the Southern Hemisphere midlatitudes, crosses the equator, and continues into the region of monsoon depression formation.

Airstream A (Fig. 6) in the conceptual model corresponds to the cross-equatorial flow in the westernmost portion of the domain as seen in the two monsoon depression formations during July 2007. This airstream originates from the eastern side of a Southern Hemisphere midlatitude anticyclone and then becomes part of the southeasterly trade wind flow. After a long west-northwestward pathway, this flow is drawn across the equator due to the lower pressure in the summer hemisphere. Once airstream A crosses the equator, it gains a more westerly component due to the Coriolis effect. If airstream A has a large southerly cross-equatorial component, it can penetrate far into the Northern Hemisphere and then interact with the eastern end of a confluent region and wrap it into a cyclonic circulation (dashed portion of Fig. 6, airstream A), which was observed in the formation of monsoon depression MD1. Airstream A has the longest Southern Hemisphere path of any of the airstreams and is also the most western (100°–125°E) airstream when crossing the equator.

Backward trajectories in Fig. 7a illustrate an airstream A that originated from the Southern Hemisphere midlatitudes (near 30°S, 140°E) and followed a path toward the northwest before crossing the equator between 120° and 130°E (Fig. 7b), where the flow began to turn east due to the Coriolis effect. Subsequently, these trajectories began to turn cyclonically between 5° and 10°N near 130°E, as airstream A entered the confluent region of trade easterlies and equatorial westerlies (MT1) in which monsoon depression MD1 formed.

The second cross-equatorial flow labeled as airstream B (Fig. 6) also originates from the eastern portion of a Southern Hemisphere midlatitude anticyclone, but has a
more direct southerly pathway into the Northern Hemisphere where the Coriolis effect turns the flow to the east. This airstream crosses the equator in the middle of the domain between 125° and 150°E. Airstream B enhances the equatorial westerlies and interacts with the trade easterlies in association with a preexisting confluent region to change the horizontal shear vorticity of the confluent region (or monsoon trough) into curvature vorticity (dashed portion of Fig. 6, B).

An excellent example of a more direct southerly airstream turning sharply to enhance the equatorial westerlies and interact with the trade easterlies is shown in Fig. 8a. The Southern Hemisphere origin of the cross-equatorial branch at 135°E (western branch) in Fig. 8a is illustrated by the backward trajectories in Fig. 8b. The origin of the cross-equatorial flow at 150°E (eastern branch) in Fig. 8a is indicated by the backward trajectories in Fig. 8c. Both Figs. 8b and 8c show that the

FIG. 8. Ensembles of 120-h HYSPLIT backward trajectories as in Fig. 7, but for the pre–Typhoon Man-Yi monsoon depression and ending times–locations at (a) 0000 UTC 6 Jul 2007–3°N, 153°E; (b) 0000 UTC 4 Jul 2007–3°S, 135°N; (c) 0000 UTC 4 Jul 2007–5°S, 150°E; and (d) 0000 UTC 6 Jul 2007–2°N, 158°E.
airstreams originated from the Southern Hemisphere. These trajectories may represent the “southerly surge,” as described by Love (1985a,b), and may be attributed to the Southern Hemisphere cyclogenesis (and anticyclogenesis) events that generate southerly flows that extend toward the equator.

A third cross-equatorial flow, airstream C (Fig. 6), originates from the merger of airstream B and the Southern Hemisphere trade easterlies. That is, the eastern side of airstream B deflects the Southern Hemisphere easterlies equatorward and results in airstream C. In the pre–Typhoon Man-Yi monsoon depression (MD$_2$) formation, this southerly flow was then deflected back into the Southern Hemisphere after crossing the equator and converging with the Northern Hemisphere trade easterlies. This process helped create a near-equatorial Southern Hemisphere cyclone labeled C$_{SH}$ in Fig. 6, as the northerly flow was deflected westward after converging with the Southern Hemisphere trade easterlies. The western branch of this clockwise circulation enhances the cross-equatorial flow of airstream C and enables the flow to penetrate farther into the Northern Hemisphere where it is able to interact with the confluent region (or monsoon trough) to form an eastern vorticity lobe.

In the MD$_2$ monsoon depression formation (Figs. 3 and 4), airstream C contributed to confluence at the eastern end of the monsoon trough and thereby enhanced the convergence and increased the cyclonic vorticity of the region that contributed to the development of the circulation. Backward trajectories in Fig. 8d indicate that this flow also originated in the Southern Hemisphere and flowed around the cyclone that was centered near 4°S, 158°E. In the conceptual model, as airstream C interacts with the eastern end of the monsoon trough and is wrapped into a broad cyclonic circulation, it creates an elliptically shaped monsoon depression circulation with two cyclonic vorticity lobes, as illustrated in Fig. 6. This airstream is a second mode of monsoon depression formation.

Compared to the Harr and Elsberry (1996) conceptual model, the new conceptual model attributes a critical role to cross-equatorial flow (airstream A or B) that penetrates into the Northern Hemisphere and enhances the strength of the equatorial westerlies. Subsequent confluence with the trade easterlies leads to convergence and contributes to a region of cyclonic vorticity. Another cross-equatorial flow (airstream A, B, or C) then interacts with the eastern end of the confluent region to create a convergent region that leads to an eastern cyclonic vorticity lobe. This second, more southerly, cross-equatorial flow then helps to combine the two vorticity lobes that form an elliptical monsoon depression circulation.

While these trajectories are useful for indicating the source regions for the airstreams entering the regions of the western or eastern vorticity maxima at the time of monsoon depression formation, they are not sufficient for describing the vorticity dynamics of the spinup of the monsoon depression. Recall that a characteristic of the monsoon depression is light winds in the interior of the circulation with outer wind maxima that are associated with the deep convective bands that wrap around the circulation. On the inside (outside) of the outer wind maxima will be cyclonic (anticyclonic) relative vorticity.

Consider the vorticity equation in the form

$$\frac{\partial \zeta}{\partial t} = -\mathbf{V} \cdot \nabla \zeta - (f + \zeta) \mathbf{V} \cdot \mathbf{V} + \frac{\partial w}{\partial x} \frac{\partial v}{\partial z} + \frac{\partial w}{\partial y} \frac{\partial u}{\partial z},$$

where frictional effects are ignored. Scale analysis of the first advective term on the right side indicates that the term on the scale of the monsoon depression will be smaller than the second convergence term, even though many of the monsoon depressions form near the equator where the Coriolis parameter $f$ is small. The beta effect term will contribute to spin up with the enhanced southerly flow on the eastern side of the monsoon depression. The tilting terms may contribute on the cloud scale but do not make an important contribution on the monsoon depression scale.

The large-scale convergence that would be consistent with the 12-h increases in relative vorticity approaching the ending point of the backward trajectories could be inferred to be a residual in the conservation of the vorticity equation. A complete convergence field inferred from such a calculation would require a large number of backward trajectories with ending points uniformly distributed over the area of maximum vorticity at the time of formation of the monsoon depression.

Vorticity fields calculated from the ECMWF analyses and forecasts are rather granular with positive and negative values oriented along bands, which must be associated with alternating values of convergence and divergence. Recall that the wave-activity fluxes in Eqs. (1) and (2) include divergence-type terms that lead to noisy fluxes that then had to be smoothed with a 1-day running mean of the 6-hourly calculations. Whereas these local maxima in convergence and divergence in the ECMWF analyses and forecasts might be aligned with the cloud bands in the monsoon depression, it cannot be assumed that such coarse-resolution analyses are properly representing the cloud-band-scale processes that are occurring in nature. That is, a full understanding of the formation and evolution to maximum intensity of the monsoon depression would require a vorticity budget analysis based on observations on convective scales as.
well as the large scales. Such an analysis is beyond the scope of this study.

The composite of 63 southerly surges from Fukutomi and Yasunari (2005) also supports the potential role of cross-equatorial flow. As the southerly flow crosses into the southern Bay of Bengal, a band of enhanced equatorial westerlies is created between 5° and 15°N in the Northern Hemisphere between 80° and 120°E (their Fig. 4b), as implied in the conceptual model in Fig. 6. Convergence of the cross-equatorial flow with northerlies also leads to an east–west band of negative outgoing longwave radiation (implying enhanced deep convection) over the same longitudinal interval. A significant difference in the Fukutomi and Yasunari (2005) study is that these enhanced equatorial westerlies do not interact with a confluent or convergent region of easterlies in the Northern Hemisphere as in the monsoon depression formation conceptual model in Fig. 6.

The primary role of airstreams A and B from the Southern Hemisphere is to accelerate the equatorial westerlies that feed into the confluent region of the monsoon depression formation area and appear to have an important role in the spinup of the western vorticity maximum. Although not observed in the 44 monsoon depression formations during 2009, a westerly wind burst as defined by Sheu and Liu (1995)² may play a similar role is accelerating the equatorial westerlies and contribute to a monsoon depression, or even twin monsoon depressions in both hemispheres (as suggested by an anonymous reviewer).

5. Applicability of the conceptual model

The applicability of this conceptual model of monsoon depression formation was examined from 1 April through 31 December 2009 utilizing high-resolution ECMWF analyses (0.25°) from the Year of Tropical Convection (YOTC) program. This period was chosen for the analysis because 44 monsoon depressions were detected between 110°E and 180° (Fig. 9). By contrast, very few monsoon depressions formed during the La Niña–type conditions that existed during the May–December 2008 and January–March 2010 periods of the YOTC archive.

a. Methodology

The first step in the observational study was to examine the high-resolution ECMWF analyses of 850-hPa vorticity and streamlines at 6-h intervals. These analysis fields were simultaneously compared with infrared satellite imagery from the MT SAT-1R (through 15 November 2009; available online at http://www.ncdc.noaa.gov/gibbs) to confirm that the cyclonic circulations in the analysis were monsoon depressions according to the JTWC (1994) and Lander (2004) definition. That is, each circulation with an associated vorticity maximum in the YOTC analyses was required to have widespread, deep convection around the periphery of the circulation (typically with two regions of concentrated convection in opposite quadrants) with little to no convection in the interior. Furthermore, the surface cyclonic circulation was validated using QuikSCAT fields (through 23 November 2009) obtained online (http://manati.orbit.nesdis.noaa.gov/datasets/QuikSCATData.php). These fields were

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² Reference provided by anonymous reviewer.
also used to confirm that the monsoon depression had light winds near the circulation center and stronger winds around the circulation periphery. Finally, the 3-hourly 0.25° TRMM precipitation (3B42 V6 derived) rates were obtained online (http://gdata1.sci.gsfc.nasa.gov/daacbin/G3/gui.cgi?instance_id=TRMM_3-Hourly). Each monsoon depression was required to have minimum precipitation near the circulation center. Thus, a ringlike pattern of precipitation in the TRMM product with a diameter similar to the cloud band in the infrared satellite imagery was used to confirm the circulation was a monsoon depression. The ringlike pattern of precipitation was not required to be continuous, and most of the cases had two precipitation maxima on opposite sides of the circulation center.

For a cyclonic circulation to be classified as a monsoon depression, three of the four datasets had to meet the criteria of a monsoon depression. If a monsoon depression formation was suspected in the YOTC analysis based on the circulation, but could not be conclusively confirmed in the satellite imagery, QuickSCAT and TRMM analyses were still checked. This procedure was necessary since the cloudiness associated with an adjacent circulation may have obscured the characteristic cloud pattern of the monsoon depression. After the mid-November 2009 termination of QuickSCAT, the primary cross-checking tool became the TRMM precipitation.

b. Analysis of airstreams

Analysis of the 44 monsoon depression formations in Fig. 9 indicated 18 (43%) formed in a similar way as the pre–Typhoon Man-Yi monsoon depression (Table 1, filled-diamond symbols in Fig. 9). These monsoon depressions form in the central and eastern portion of the domain (130°E–180°). Except for the 1800 UTC 31 July and 0600 UTC 6 August 2009 cases, these monsoon depression formations formed quite close to the equator, especially during the early or late season (Table 1). The 6 August outlier formation occurred at 19°N when two tropical cyclones in the western region of the domain, at a similar latitude as the monsoon depression, were influencing the cross-equatorial flow. Notice in Table 1 that the cross-equatorial flows could originate from the region between Southern Hemisphere midlatitude cyclones and anticyclones located across the domain (90°E–180°).

This most frequent mode of monsoon depression formation emphasizes the importance of airstream C, which occurs in the eastern domain between 150°E and 180° (Table 1). In the case shown in Fig. 10, the eastern portion of airstream B, which originated from a Southern

<table>
<thead>
<tr>
<th>Time</th>
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<th>Anticyclone center</th>
<th>Cyclone center (C_SH)</th>
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<td>Lat</td>
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<td>29°S</td>
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</tr>
<tr>
<td>1200 UTC 27 Nov 2009</td>
<td>1°N</td>
<td>159°E</td>
<td>Undefined</td>
</tr>
</tbody>
</table>
Hemisphere anticyclone, merges with the Southern Hemisphere trade easterlies, and enhances the southerly flow around the Southern Hemisphere cyclone near 5°S, 160°E. Note the similar role of the Southern Hemisphere cyclone as in the July 2007 monsoon depression MD2 formation (Fig. 3).

Two other examples in which airstream C played an important role in the formation of the eastern vorticity lobe are shown in Figs. 11a and 11b. The monsoon depression in Fig. 11b formed at 0600 UTC 29 September 2009 in association with the cross-equatorial flow from the Southern Hemisphere cyclone. This monsoon depression later transitioned into Typhoon Melor (0000 UTC 30 September 2009). As indicated by the 120-h backward trajectories for this monsoon depression (Fig. 12a), the primary sources were from the south and east. The backward trajectory ensemble in Fig. 12b ends near the equator (southern branch of Fig. 12a) and highlights airstream C, which is evident from the clockwise flow around the Southern Hemisphere cyclone. The final backward trajectory in Fig. 12c was from the edge of this Southern Hemisphere cyclone and highlights that the flow into the Southern Hemisphere cyclone was predominantly from the Southern Hemisphere easterlies.

In 12 of the 44 cases during 2009 (asterisk in Fig. 9), airstream C did not have an associated Southern Hemisphere cyclone (Table 2). This variant of airstream C is hereafter referred to as the airstream C* mode of monsoon depression formation and occurs in the eastern portion of the domain (170°E–180°). In this new scenario, a cross-equatorial flow interacts with the Northern Hemisphere trade easterly flow. Southeasterlies begin to develop as the cross-equatorial flow begins to be deflected to the east due to the Coriolis effect, but the strength of the trade easterlies in the Northern Hemisphere is an important factor in preventing the formation of westerlies. When southeasterly flow is established in both hemispheres, a confluent region develops that leads to a small cyclonic vorticity maximum. As the initial cross-equatorial flow ceases, the Northern Hemisphere trade easterlies are reestablished and the new cyclonic vorticity maximum may be characterized as a wave in the easterlies. It is this cyclonic vorticity maximum that subsequently develops into a monsoon depression when a second cross-equatorial flow interacts with it. This second cross-equatorial flow event is then labeled as airstream C*.

The monsoon depressions that formed from airstream C* occurred mainly between 145° and 170°E (Table 2).
An exception was the first monsoon depression that formed by airstream $C^*$ in 2009, which was early in the season (26 May) and formed farther west as trade easterslies existed in both hemispheres over the majority of the domain. These monsoon depressions also tend to form at latitudes below $10^\circ N$, with the exceptions of the 0000 UTC 15 August and 1200 UTC 11 September monsoon depressions, which formed at $12^\circ$ and $14^\circ N$, respectively. Although the majority of the monsoon depressions that form from this airstream have an elliptical shape, three from 2009 were more circular in shape.

The monsoon depression (Fig. 11c) that formed at 0600 UTC 11 September 2009 from the interaction of a wave in the easterlies and airstream $C^*$, transitioned into Typhoon Choi-Wan (1800 UTC 12 September 2009). In this case, no Southern Hemisphere cyclone was present (cf. with Figs. 11a and 11b), and the flow across the equator penetrated far enough north to interact with the wave in the easterlies. Note that the Southern Hemisphere easterlies were first deflected northward by airstream B as in the original airstream C discussion. However, airstream $C^*$ differs from the original airstream C because it penetrates far enough into the Northern Hemisphere such that the flow is not deflected back across the equator by the trade easterlies, and a Southern Hemisphere cyclone does not form. Two examples of the
The eight (18%) monsoon depression formations during 2009 in which airstream B had a dominant contribution are listed in Table 3 and are indicated by a filled triangle in Fig. 9. The formations related to airstream B occur across the entire domain from 3° to 16°N and 125° to 170°E (Table 3). As in the earlier modes, these monsoon depressions tend to have an elliptical shape. A characteristic of airstream B in the conceptual model (Fig. 6) was that it has a more direct southerly path to the Northern Hemisphere. In the examples in Figs 10 and 11a (western arrow, airstream B), this cross-equatorial flow enhanced the equatorial westerlies after it crossed
the equator. If a confluent region existed downstream of where this flow crosses the equator, airstream B was considered to increase the convergence needed to transition the confluent region into an elliptical cyclonic circulation that is a monsoon depression (Fig. 6). The monsoon depression that formed on 0000 UTC 22 October 2009 (Fig. 11a) was comparable to the July 2007 monsoon depression MD2 case. The backward-trajectory ensemble

### Table 2

As in Table 1, but for monsoon depressions that formed from airstream C*, and there is no column for Southern Hemisphere cyclones. Either an elliptical (E) or circular (C) shape of the monsoon depression is listed in the last column.

<table>
<thead>
<tr>
<th>Airstream C*</th>
<th>MD center</th>
<th>Southern Hemisphere anticyclone center</th>
<th>Shape</th>
</tr>
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<tbody>
<tr>
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<td>Long</td>
<td>Lat</td>
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<tr>
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<td>0000 UTC 7 Jul 2009</td>
<td>4°N</td>
<td>161°E</td>
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<td>1800 UTC 18 Jul 2009</td>
<td>4°N</td>
<td>169°E</td>
<td>26°S</td>
</tr>
<tr>
<td>0600 UTC 13 Aug 2009</td>
<td>9°N</td>
<td>145°E</td>
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<td>0600 UTC 11 Sep 2009</td>
<td>14°N</td>
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<td>0600 UTC 27 Dec 2009</td>
<td>4°N</td>
<td>145°E</td>
<td>34°S</td>
</tr>
</tbody>
</table>

**Fig. 13.** Wave-activity flux vectors (m² s⁻¹) as in Fig. 5, but at (a) 1200 UTC 9 Sep and (b) 0000 UTC 10 Sep 2009, and the boxes highlight the cross-equatorial wave-activity fluxes at two times prior to the formation of the pre–Typhoon Choi-Wan monsoon depression at 14°N, 155°E.
and wave-activity flux progressed in the same fashion as the pre–Typhoon Man-Yi case (Figs. 5 and 8) and, therefore, are not shown.

Finally, cases in which airstream A had a primary role in the formation of MD$_1$ from July 2007 and four 2009 monsoon depressions are listed in Table 4 and indicated in Fig. 9 with a filled circle symbol. In general, these monsoon depressions formed in the western portion of the domain near the Philippines and tended to have a more circular shape (Table 4) rather than the preference for an elliptical shape as in the other scenarios. The example of airstream A from the 2009 dataset (Fig. 10) had a more northward path (A$_1$) and a path that quickly turned to become equatorial westerlies (A$_2$). It was this airstream A$_3$, which was also joined by an airstream B, that provided the confluence with the trade easterlies and eventually the convergence that contributed to the spinup of a western vorticity lobe and ultimately transitioned the confluent region into a cyclonic circulation.

Monsoon depression formations from airstream A may also occur, as in the July 2007 MD$_1$ case (Fig. 3) in which the cross-equatorial flow penetrates to higher latitudes (around 10$^\circ$N) (Fig. 11d and Table 4). How far north the formation occurs depends on the strength of the cross-equatorial flow relative to the strength of pre-existing westerlies (Fig. 11d) in the Northern Hemisphere (path A$_1$ in Fig. 10). The monsoon depression in Fig. 11d formed from airstream A at 0000 UTC 25 July 2009 in a manner similar to the July 2007 monsoon depression MD$_1$ (Figs. 5 and 7). The Southern Hemisphere anticyclone was centered at 30$^\circ$S, 150$^\circ$E at the time of formation (Table 4), with a cross-equatorial flow that still extended from the anticyclone to the monsoon depression at 11$^\circ$N. The backward-trajectory ensemble and wave-activity flux convergence pattern for this case were comparable to the first July 2007 monsoon depression (Figs. 7 and 5), so they are not shown.

Two monsoon depressions (5%) could not be categorized by the airstream from which they formed because they were already monsoon depressions when they entered the study domain (plus signs in Fig. 9). Since the formation of these circulations occurred east of 180$^\circ$, these three monsoon depressions could not be classified as having originated from a particular airstream.

Of the 44 monsoon depressions during 2009 for which the conditions during formation could be established, 41 had cross-equatorial flow from the Southern Hemisphere with an airstream that could be matched with the new conceptual model in Fig. 6. As demonstrated in Fig. 10, more than one airstream may be present during formation. However, the airstream that was the primary contributor to the formation of each monsoon depression during 2009 has been summarized in Tables 1–4. The most common of these airstreams was airstream C, which appeared to be associated with the formation of the broad, elliptically shaped cyclonic circulations. In many of those cases, airstreams A and B were also present and contributed to the enhancement of the equatorial westerlies that subsequently interacted with a confluent region and thus contributed to monsoon depression formation.

### Table 3. As in Table 2, but for monsoon depressions that formed from airstream B.

<table>
<thead>
<tr>
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<th>Southern Hemisphere anticyclone center</th>
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<tr>
<td>0000 UTC 17 May 2009</td>
<td>4$^\circ$N, 123$^\circ$E</td>
<td>34$^\circ$S, 135$^\circ$E, E</td>
</tr>
<tr>
<td>1800 UTC 22 Jul 2009</td>
<td>4$^\circ$N, 165$^\circ$E</td>
<td>25$^\circ$S, 174$^\circ$E, E</td>
</tr>
<tr>
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<td>6$^\circ$N, 144$^\circ$E</td>
<td>26$^\circ$S, 178$^\circ$E, E</td>
</tr>
<tr>
<td>1800 UTC 22 Aug 2009</td>
<td>16$^\circ$N, 142$^\circ$E</td>
<td>23$^\circ$S, 149$^\circ$E, E</td>
</tr>
<tr>
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<td>12$^\circ$N, 134$^\circ$E</td>
<td>24$^\circ$S, 140$^\circ$E, E</td>
</tr>
<tr>
<td>1800 UTC 4 Oct 2009</td>
<td>9$^\circ$N, 154.5$^\circ$E</td>
<td>30$^\circ$S, 129$^\circ$E, E</td>
</tr>
<tr>
<td>0000 UTC 29 Oct 2009</td>
<td>3$^\circ$N, 166$^\circ$E</td>
<td>33$^\circ$S, 151$^\circ$E, E</td>
</tr>
</tbody>
</table>

### Table 4. As in Table 2, but for monsoon depressions that formed from airstream A.

<table>
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<td>1200 UTC 3 Jul 2007</td>
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<td>14$^\circ$N, 134$^\circ$E</td>
<td>30$^\circ$S, 90$^\circ$E, C</td>
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</table>
6. Summary and conclusions

In summary, the new conceptual model (Fig. 6) of monsoon depression formation in the western North Pacific assigns a critical role to cross-equatorial flows that penetrate into the Northern (summer) Hemisphere. One type of cross-equatorial flow enhances the equatorial westerlies that become part of a confluent region with the trade easterlies and is hypothesized to increase the horizontal shear and curvature vorticity of the region. A second type of cross-equatorial flow more directly interacts with the eastern end of the confluent region to form an eastern cyclonic vorticity lobe and contributes to wrapping the flow into a broad cyclonic circulation.

Examination of a sample of 44 monsoon depression formations from April to December 2009 confirmed the role of these cross-equatorial flows in the new conceptual model of monsoon depression formation. However, another scenario of monsoon depression formation that involved airstream \( C_\alpha \) was detected in the analysis of the 2009 sample. The fundamentals of the conceptual model still apply in this scenario, with the primary difference being that the confluent region is a wave in the easterly flow that appears to have been generated from an earlier cross-equatorial flow farther to the east. These cases have shown that the combination of a confluent region (or monsoon trough) and a southerly flow are frequently associated with monsoon depression formation. That is, all of the monsoon depressions for which formation conditions could be established in the 2009 sample had at least one of the airstreams \( A, B, \) or \( C (C_\alpha) \) interacting with a confluent region. This qualitative analysis of the high-resolution ECMWF analyses was further confirmed by means of wave-activity flux calculations and backward-trajectory ensembles.

Another inference from the 2009 cases is that the locations of the Southern Hemisphere midlatitude anticyclones and cyclones dictate the cross-equatorial airstream that is involved in the formation of the observed western North Pacific monsoon depressions. An examination of how the amplitude and strength of these Southern Hemisphere anticyclones and cyclones changes the character of the cross-equatorial airstream is beyond the scope of this study. However, the backward trajectories from the two 2007 monsoon depression formations, as well as that of 2009, do establish the linkages to the cross-equatorial flows and the Southern Hemisphere anticyclone. Furthermore, Fukutomi and Yasunari (2005) form composites of the 200-hPa wind anomalies and use potential vorticity anomalies on the 315-K potential temperature surface to establish the connection between the amplifying midlatitude wave train and the 850-hPa southerly surges. Thus, the primary contribution for the operational forecasters from this study is that they should also monitor the Southern Hemisphere for evidence of southerly flow of the three types described, as previous guidance had only been to monitor the Northern Hemisphere easterlies and westerlies.

Wave-activity flux calculations indicate that kinetic energy is being propagated from the cross-equatorial flow initiated in the Southern Hemisphere and across the equator into the region of the monsoon depression formation. Whether or not the cross-equatorial airstream then interacts with a Northern Hemisphere confluent region, which is the second necessary condition for this conceptual model, determines if a monsoon depression will form. Further studies of the necessary, but not sufficient, conditions and the physical mechanisms for monsoon depression formation are in progress and will be communicated later.

Acknowledgments. Support for Prof. R. Elsberry was provided by the Office of Naval Research Marine Meteorology section. Dr. Karl Pfeiffer and Dr. Zhuo Wang have been very helpful in the code work development for data analysis. The authors gratefully acknowledge the ECMWF for the provision of the YOTC dataset (http://data-portal.ecmwf.int/data/d/yotc_od/); the TRMM mission scientists and associated NASA personnel for the production of the TRMM data and visualizations that were produced with the Giovanni online data system, which is developed and maintained by the NASA GES DISC (http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=TRMM_3-Hourly); the NOAA/Air Resources Laboratory (ARL) for the provision of the HYSPLIT transport and dispersion model and the READY website (http://www.arl.noaa.gov/ready.php); and the NOAA/NESDIS/Center for Satellite Applications and Research for the provision of the QuikSCAT data from their web site (http://manati.orbit.nesdis.noaa.gov/datasets/QuikSCATData.php). This study benefited from the comments and suggestions of the anonymous reviewers. Mrs. Penny Jones provided assistance in the manuscript preparation.

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