## 17D.3 THE WESTERN NORTH PACIFIC MONSOON DEPRESSION FORMATION AND STRUCTURE

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### 1. INTRODUCTION

Following the definition of the Joint Typhoon Warning Center (JTWC), the 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 (Elsberry 2002). In the western North Pacific, monsoon depressions provide a cyclonic vorticity environment in which mesoscale convective systems (MCS) and their associated mesoscale convective vortices (MCV) can develop, persist, and lead to tropical cyclone formation. Relatively little is known about the formation of the monsoon depression circulation and its structure, which is essential to understand its role in tropical cyclone formations, and to understand why some monsoon depressions lead to tropical cyclone formation and others do not.

Harr et al. (1996) used aircraft observations during the Tropical Cyclone Motion (TCM-93) field experiment during 1993 to describe a monsoon depression that eventually intensified to a tropical depression and became Typhoon Robyn. They suggested that a monsoon depression may form in the convergent flow between the equatorial westerlies to the south and trade wind easterlies to the north. This process also occurred during early July 2007, when a monsoon depression became Typhoon Man-Yi. It is this latter case that will be the focus in this study.

It is hypothesized that the monsoon depression forms in a convergence zone that arises due to the interaction of two flows: equatorial westerlies extending eastward, and tradewind easterlies extending westward. One specific mode of monsoon depression development is when the convection bands associated with these two flows wrap around the convergence. The enhanced wind flows in the tradewind easterlies and the equatorial westerlies contribute to the environmental cyclonic vorticity, as the shear vorticity of the two flows contribute to the curvature vorticity of the circulation. The associated surface pressure falls are presumably due to the forced subsidence between the respective regions of convection and what leads to flow enhancement (R. Elsberry personal communication with G. Holland 1990). This evolution leads to a large, closed circulation with weak winds at the center and stronger winds along the perimeter, which satisfies the JTWC definition of a monsoon depression.

An alternate hypothesis of the development of the monsoon depression is due to the barotropic instability of the monsoon trough environment, as in the Guinn and Schubert (1993) and Ferreira and Schubert (1997) simulations. As simulated in those barotropic numerical studies, an unstable PV gradient leads to waves that grow barotropically, with the poleward side of their idealized monsoon trough being more favorable. It is expected that a combination of both baroclinic and barotropic processes contribute to create the monsoon depression. Harr et al. (1996) demonstrated that the monsoon trough was the baroclinic zone in which the monsoon depression formed in the pre-Typhoon Robyn scenario.

The objective in this first phase of research is to document the sensitivity of the forecasts of the formation of the pre-Man-Yi monsoon depression to the initial conditions and the model dynamics and physics. Two mesoscale models will be utilized: (i) NCAR/PSU Mesoscale Model version 5 (MM5) (version 3, release 3-5); and (ii) Weather and Research Forecast (WRF) model from NCAR. The initial and lateral boundary conditions for the MM5 and the WRF models are from the NCEP Global Forecast System (GFS). Since the special characteristics of the monsoon depression are the strong winds in the cloud bands at large radii, the wind field and the precipitation are the primary focus for these model predictions. Satellite-based precipitation estimates from the TRMM and from the NRL blended-satellite precipitation products will be used for verification of the model-predicted precipitation. The NRL blended-satellite precipitation product is a real-time blend of all operational passive microwave satellite products and the operational geostationary satellites at

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0.25-degree resolution. Satellite images (MTSAT) from this time period are also used to assist in verification of the location and size of the developing monsoon depression. These images were obtained from the National Climatic Data Center satellite archive.

The time period of the pre-Typhoon Man-Yi monsoon depression formation is considered to be 1200 UTC 3 July 2007 – 1800 UTC 6 July 2007. The domains were identical for each model with a grid spacing of 81 km in the outermost domain, 27 km in the middle domain, and 9 km in innermost domain. The physics schemes for the two models were chosen so that the two models were as similar as possible. The physics options that were chosen for each model are displayed in Table 1.

Table 1: Listing of selected physics options.

| | MM5 | WRF |
|---|---|---|
| Cumulus Parameterization | New Kain - Fritsch | Kain - Fritsch |
| PBL Scheme | ETA | YSU |
| Explicit Moisture Scheme | Single-moment 6 class | Goddard |
| Radiation Scheme | RRTM & Dudhia | RRTM & Dudhia |

RRTM: Rapid Radiative Transfer Model

## 2. COMPARISON OF MODEL PREDICTIONS

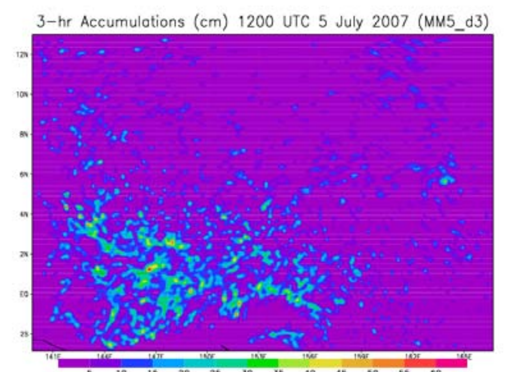
### 2.1 *Precipitation*

The predicted evolution of precipitation was first subjectively compared with the MTSAT satellite imagery, at 3-hour intervals, to validate each model. The digital NRL blended-satellite precipitation product was then used as the primary qualitative validation source using 3-hour accumulation intervals. A primary interest is in the embedded convective regions, especially their tracks and how they interacted with the evolving monsoon depression circulation.

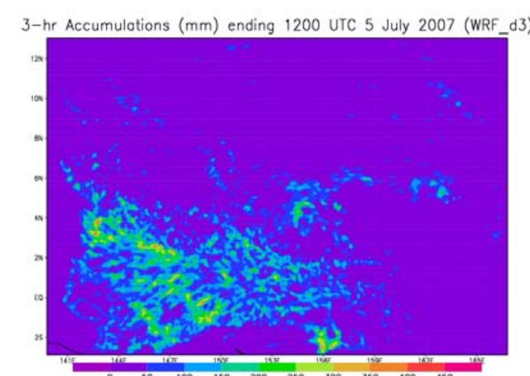
Both models had similar overall convective patterns similar to the satellite data sets throughout the time period studied. Initially, MM5 seemed to be more sensitive as it displayed more widespread precipitation of small accumulations. Upon closer investigation, the spatial coverage predicted by MM5 agreed better with the precipitation regions shown by the satellite than WRF. In general, WRF under-predicted the spatial coverage of precipitation. Therefore, only the primary regions of precipitation represented in the satellite imagery were the focus as both models represented these primary regions. However, the locations of the primary precipitation regions were slightly to the north of the satellite positions in both MM5 and WRF. The WRF-predicted precipitation amounts were of similar magnitude as the satellite 3-hour accumulation rates. By contrast, the precipitation rates in MM5 tended to be slightly higher than the satellite-derived 3-hour accumulations.

During 1800 UTC 3 July to 1500 UTC 5 July, the monsoon trough was present as a band of convection extending northeast to southeast. Low-level convergence was evident in the wind field in both models.

On 1200 UTC 5 July, both models predicted a band of convection along 6°N would enter the domain from the east in a region of trade easterlies as seen in Figure 1. This convective region was then predicted to move westward rather quickly. Meanwhile, a loosely organized region of convection was approaching from the west. The juxtaposition of the two convective regions occurred around 0900-1200 UTC 6 July. In terms of the convective pattern, the pre-Man-Yi monsoon depression had thus formed by 1800 UTC 6 July 1800.




(a)



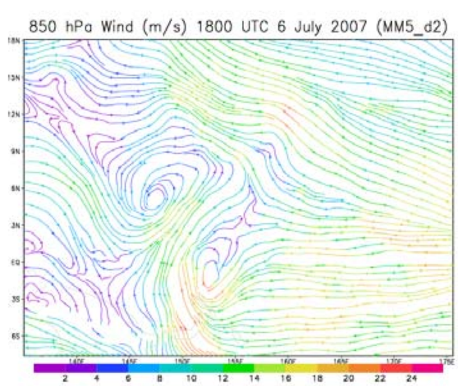

(b)

Figure 1: 3-hr accumulation in millimeters ending at 1200 UTC 5 July 2007 as predicted by (a) the MM5 9 km domain and (b) the WRF 9 km domain. The leading edge of the westward moving precipitation can be seen at 6N in the eastern portion of the domains.

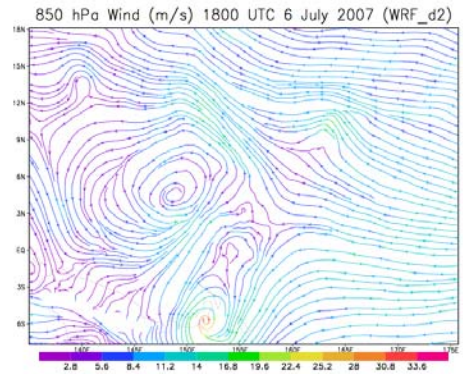
## 2.2 *Wind Field Analyses*

The predicted characteristics (strength of winds, radii of maxima, vertical wind shear, etc.) of the wind fields are compared with the monsoon depression circulation in the GFS analyses during the period. A special interest is the hypothesized flow enhancement in the equatorial westerlies and trade easterlies.

As in the general precipitation patterns, the wind patterns predicted by the two models is similar. Initially a northwest-to-southeast region of convergence exists in all domains since these fields were extracted from the GFS analysis field. A small cyclonic circulation that was present in the 1800 UTC 3 July initial conditions continued to exist on 4 July and slowly migrated westward. Since this circulation is rather small, it does not meet the definition of the monsoon depression despite having some aspects of the characteristic wind structure. This circulation combines with another circulation approaching from the west early on 6 July (0200-0600 UTC). It is this combination of cyclonic circulations that leads to the monsoon depression formation. Once this combination occurs, the circulation meets all requirements of the JTWC definition of a monsoon depression. From 0600 UTC to 1800 UTC 6 July, the monsoon depression circulation becomes more organized and the outer winds begin to increase. The monsoon depression can be seen in figure 2.




(a)




(b)

Figure 2: 850 hPa wind fields on 1800 UTC 6 July 2007 as depicted by the (a) MM5 27 km domain and (b) the WRF 27 km domain.

The MM5 and WRF models have some differences as to how the two cyclonic circulations merged. In the MM5, the convection in the trade easterlies was accompanied by a weak cyclonic circulation that had entered the domain at the same time as the precipitation embedded in the trade easterlies (1200 UTC 5 July). The western cyclonic circulation had remained fairly stationary. Following the time at which this western circulation combines with the westward-moving circulation, the new larger circulation begins to move west-northwest.

Whereas the WRF model also predicted the circulation that MM5 developed and moved it westward, this circulation became the easternmost circulation as WRF developed another small cyclonic circulation to its west. In MM5, the original circulation was the western-most of the two. Although the two WRF circulations merge during the same time period as predicted in MM5, this occurred at 4-5°N in WRF, which was slightly south of the merger in MM5 (5-6°N). At most, the positions in the two models deviated by 1 degree of latitude and 2 degrees of longitude with the circulation in MM5 to the north and west of the circulation in WRF. However, the 6-hour GFS analyses do not contain the merger event. The merged cyclonic circulation appears in the GFS 0600 UTC 6 July analysis to have resolved just the signature of the two circulations, however, the origin of the merged circulation is not apparent from the GFS analyses.

The magnitude of the winds was also monitored to determine whether flow enhancement was predicted in the trade easterlies and equatorial westerlies. The flow was enhanced in MM5 both during and after the merger of the two small cyclonic circulations. Although this flow enhancement was also predicted in WRF the WRF model also predicts some flow enhancement during the time leading up to the merger.

Both models had similar velocities for the inner and outer wind radii of the circulation. The weak inner winds were consistently less than 6 m/s after the merger (0600 UTC 6 July) of the two smaller circulations. The winds at larger radii for both models ranged from 8 – 16 m/s during the merger through the end of the observation period, 1800 UTC 6 July. The radius of maximum winds of about 10-11 degrees of latitude was similar in both mesoscale models and the GFS analyses.

Vertical cross-sections in the monsoon depression formation environment indicate the vertical shear over the region was minimal through the time of development. These cross-sections were made through the monsoon depression circulation as well as through the pre-formation environment. The more significant vertical shear seemed to be above 500 hPa at most times and locations.

### 2.3 *Vorticity*

Finally, the predicted evolution and structure of the vorticity fields is examined to determine the contribution to the environmental cyclonic vorticity as the flows converge. This vorticity structure is considered to be a key factor in how a tropical cyclone can form from a monsoon depression.

The predicted vorticity fields of the two models were rather similar. The initial circulation (well-tracked beginning 4 July in MM5 and from the start in WRF) had a maximum positive vorticity just ahead of it, which can be tracked through the merger to become part of the monsoon depression. However, this is the only significant vorticity maximum that can be tracked through a majority of the time period.

Early in the integration a gradient of vorticity existed as expected in the region of monsoon trough convergence. This gradient breaks down as the convergent flow is modified by the development of the monsoon depression circulation. No traceable vorticity maximum was associated with the convection that enters on 1200 UTC 5 July. As the convection moves west, a vorticity maximum becomes apparent that then merges with the original vorticity maximum from 4 July. At 1800 UTC 6 July, the monsoon depression has formed and a broad relative vorticity maximum is associated with the circulation in all models as expected.

## 3. CONCLUSIONS

As expected there was little difference between the representations of the pre-Typhoon Man-Yi monsoon depression formation between the MM5 and WRF mesoscale models. The models were similar in the representation of circulation, precipitation and vorticity. The differences between the two models were in the position of the key features and the amount of rainfall predicted.

The goal of the inter-comparison of these models was to select the model that provides the best description of monsoon depression formation, and then use those model fields to diagnose the physics that lead to a monsoon depression in future studies. Either model could be used for further examination of monsoon depression formation. The future model simulations are expected to provide additional guidance as to the evolution and structure of the monsoon depressions in the western North Pacific, which will be useful for the Tropical Cyclone Structure (TCS08) field experiment during August and September 2008.

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