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Formation, Structure Change, and  
Predictability in the Western North Pacific  
Region and TCS08 Experiment Support**

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## **A Multiscale Study of Tropical Cyclone Formation, Structure Change, and Predictability in the Western North Pacific Region and TCS08 Experiment Support**

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### **LONG-TERM GOALS AND OBJECTIVES**

The overarching objectives of this research project are to obtain an improved understanding of the formation, predictability and structure change of tropical cyclones in the Western Pacific region. During the second year of this project multiple cases have been analyzed in support of the Tropical Cyclone Structure 2008 (TCS08) field campaign. Because of space constraints, only a brief summary of these extensive results is presented here.

### **APPROACH**

In recent work the P.I. and two of his collaborators have developed a new paradigm of tropical cyclogenesis that occurs within the critical layer of easterly waves for the Atlantic and East Pacific Basins (Dunkerton, Montgomery & Wang 2008). The Kelvin's cat's eye within the critical layer of a tropical easterly wave was hypothesized to be important to tropical storm formation because:

**H1:** Wave breaking or roll-up of the cyclonic vorticity and lower-tropospheric moisture near the critical surface in the lower troposphere provides the moist vorticity seedling for TC formation;

**H2:** The cat's eye is a region of approximately closed circulation, where air is repeatedly moistened by deep moist convection and protected to some degree from dry air intrusion;

**H3:** The parent wave is maintained and possibly enhanced by diabatically amplified mesoscale vortices within the wave.

The entire sequence is likened to the development of a marsupial infant in its mother's pouch, and for this reason has been dubbed the 'marsupial paradigm.' For the TCS08 field experiment, we have hypothesized that the Marsupial Paradigm may be applicable under certain circumstances in the Western Pacific sector and that easterly waves or other westward propagating disturbances may be important ingredients in the birthing process of typhoons. Our initial analysis of typhoons Man-yi,

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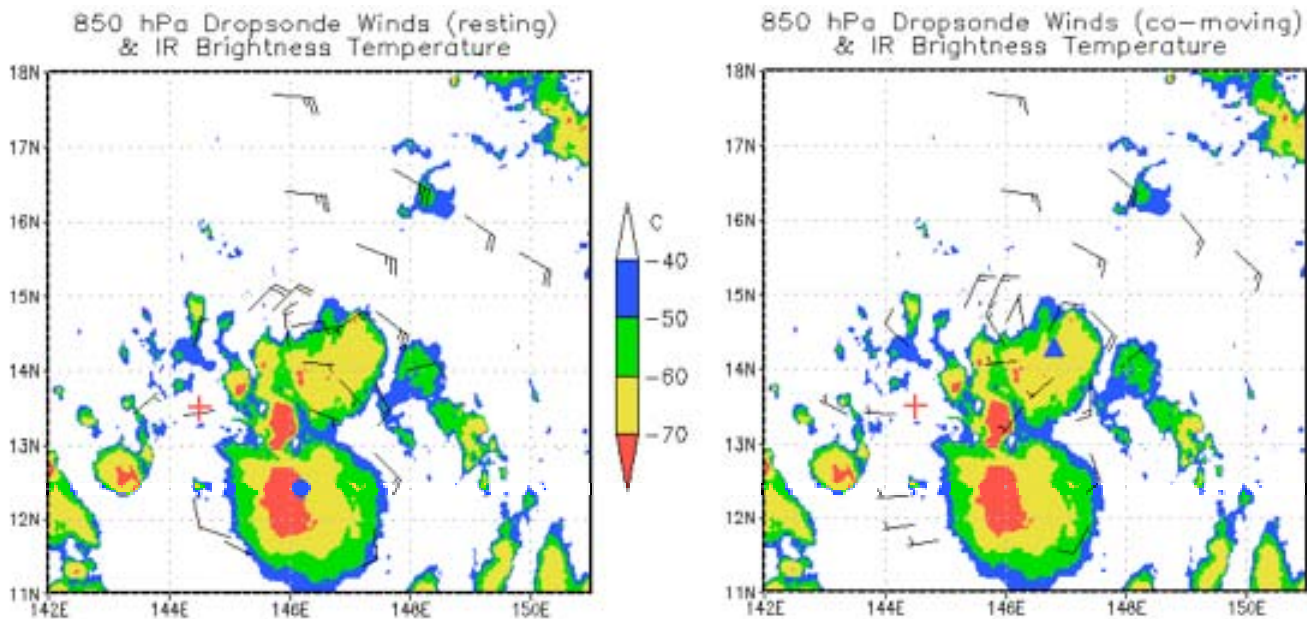
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Nuri, and Hagupit suggests that the paradigm is applicable and should provide useful forecast guidance to U.S. Naval operations in this region.

## WORK COMPLETED / RESULTS

Preliminary results from analysis of Typhoon Nuri were detailed in the previous annual report. Continued analysis has strengthened the conclusions that Nuri's genesis occurred near the "sweet spot" occurring at the intersection of the wave's trough and critical latitude.

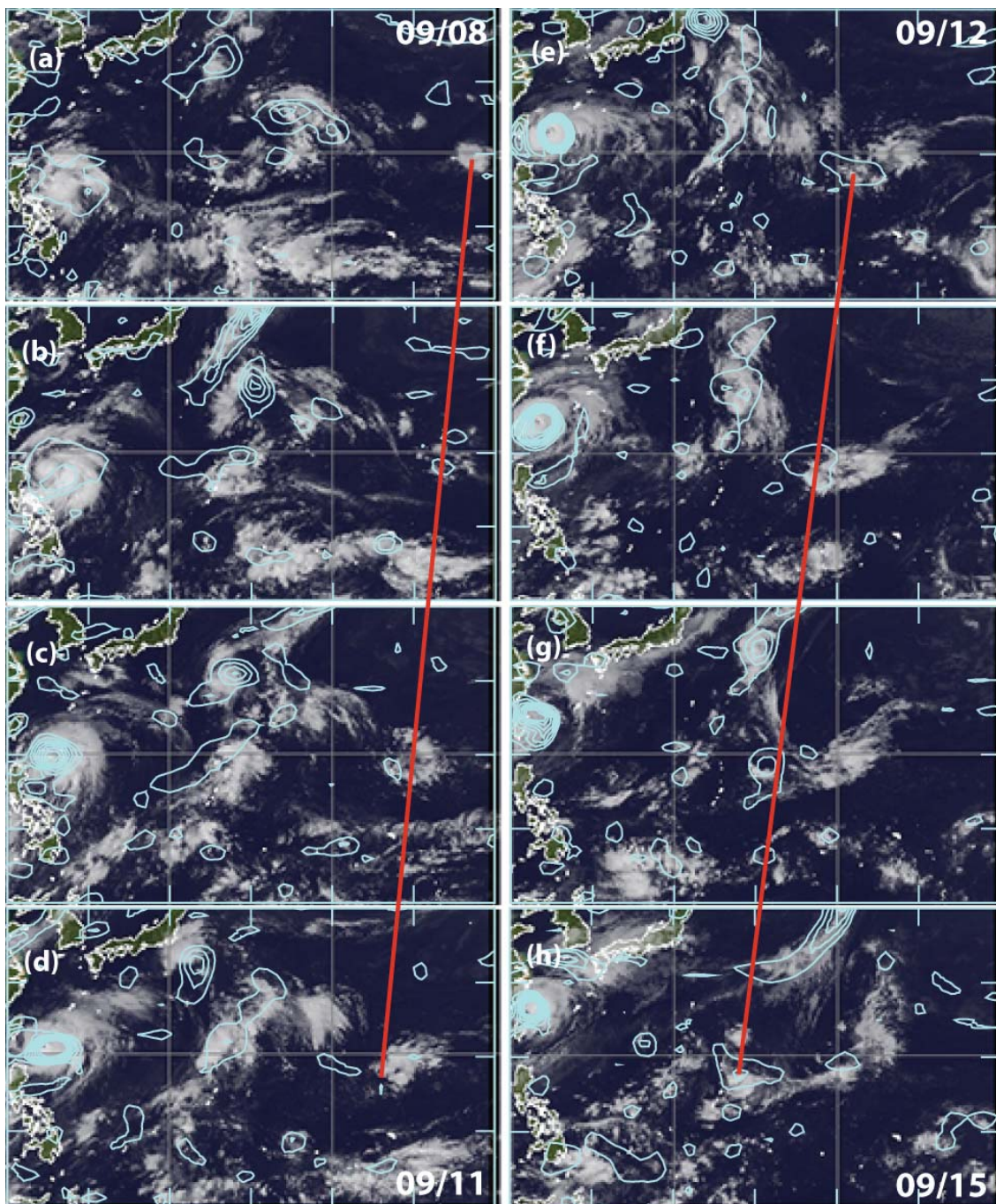


**Figure 1. Combined USAF C130 and NRL P3 850 hPa dropwindsonde observations from the Nuri genesis flight centered on 00Z 16 August overlaid with MTSAT IR data. Wind barbs are in the earth-relative (left) and co-moving (right) frames. Wind speeds are in knots with a full barb representing 10 kt. Magenta barbs indicate winds with a westerly component in the earth-relative frame. The red cross represents the location of Guam and the blue triangle represents the location of the low-level cyclonic circulation center in the co-moving frame. The C130 flight was centered along the wave trough axis and collected data throughout the 'pouch' region.**

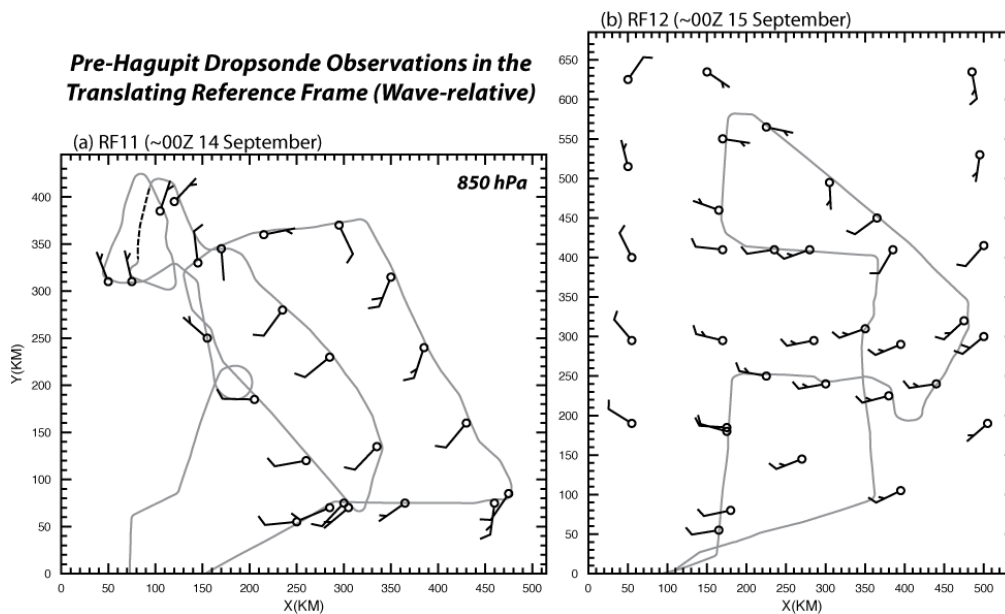
Figure 1 depicts the dropwindsonde data from one of these pre-Nuri flights overlaid with MTSAT IR data. The left panel represents 850 hPa wind barbs in the earth-relative frame and the right panel shows the data in the co-moving frame. The red cross is the location of Guam. When viewed in the earth-relative frame the aircraft observations depict an open wave, confirming that the precursor disturbance to Typhoon Nuri is of the easterly wave type. The blue triangle in Fig. 1b indicates the approximate location of the dropwindsonde-derived closed low-level cyclonic circulation in the co-moving frame. In the co-moving frame, the dropwindsonde data indicates a closed low-level cyclonic circulation at 146.7 E, 14.3 N. We believe this to be the first observational evidence of the coherent cat's eye circulation that eventually becomes Typhoon Nuri.

A similar analysis has been performed with observational data from Typhoon Hagupit during the pre-depression stage. The precursor wave disturbance was initially identifiable as a discrete patch of high moisture in the total precipitable water (TPW) fields on 7 September near 180 E (not shown). No identifiable convective activity was evident in the geostationary satellite imagery, nor any detectable wave structure or vorticity maximum in the global analysis fields. After the TPW anomaly crossed the date line, convection began to flare and became trackable in the MTSAT infrared imagery (Figure 2), propagating zonally toward the TCS-08 aircraft domain. An 850 hPa vorticity maximum was first apparent in the global model analysis around 00 UTC 09 September; this elevated vorticity anomaly gradually increased in amplitude as the wave moved westward (cyan overlay in Figure 2). These analyses suggest that Hagupit formed also from an easterly-type wave, similar to Nuri.

At ~00 UTC 14 September 2008 the tropical disturbance, which later developed into Typhoon Hagupit, exhibited a classical ‘open-wave’ structure at the NRL P3 flight level (~650 hPa). However, our initial analyses of the dropsonde winds shown in Figure 3a reveal a weak, closed low-level circulation below the aircraft in the co-moving frame that moves with the tropical disturbance. A two-plane mission 24 hours later revealed that the circulation was persistent as the disturbance moved into a lower shear environment and exhibited an increase in convective activity (Figure 3b). The initial mission into pre-depression Hagupit (2008) occurred *four days prior* to the Joint Typhoon Warning Center tropical cyclone formation alert, after which the tropical disturbance went on to intensify into a typhoon causing over 1 billion dollars in damage and 67 deaths.



**Figure 2.** MTSAT IR imagery at 0030 UTC from 8 – 15 September and 850 hPa relative vorticity from the GFS FNL analysis for the pre-Hagupit disturbance. The red line follows the convective activity associated with the pre-Hagupit disturbance as it propagates westward. Cyan vorticity contours are every  $4 \times 10^{-5} \text{ s}^{-1}$  with a minimum  $2 \times 10^{-5} \text{ s}^{-1}$  contour.

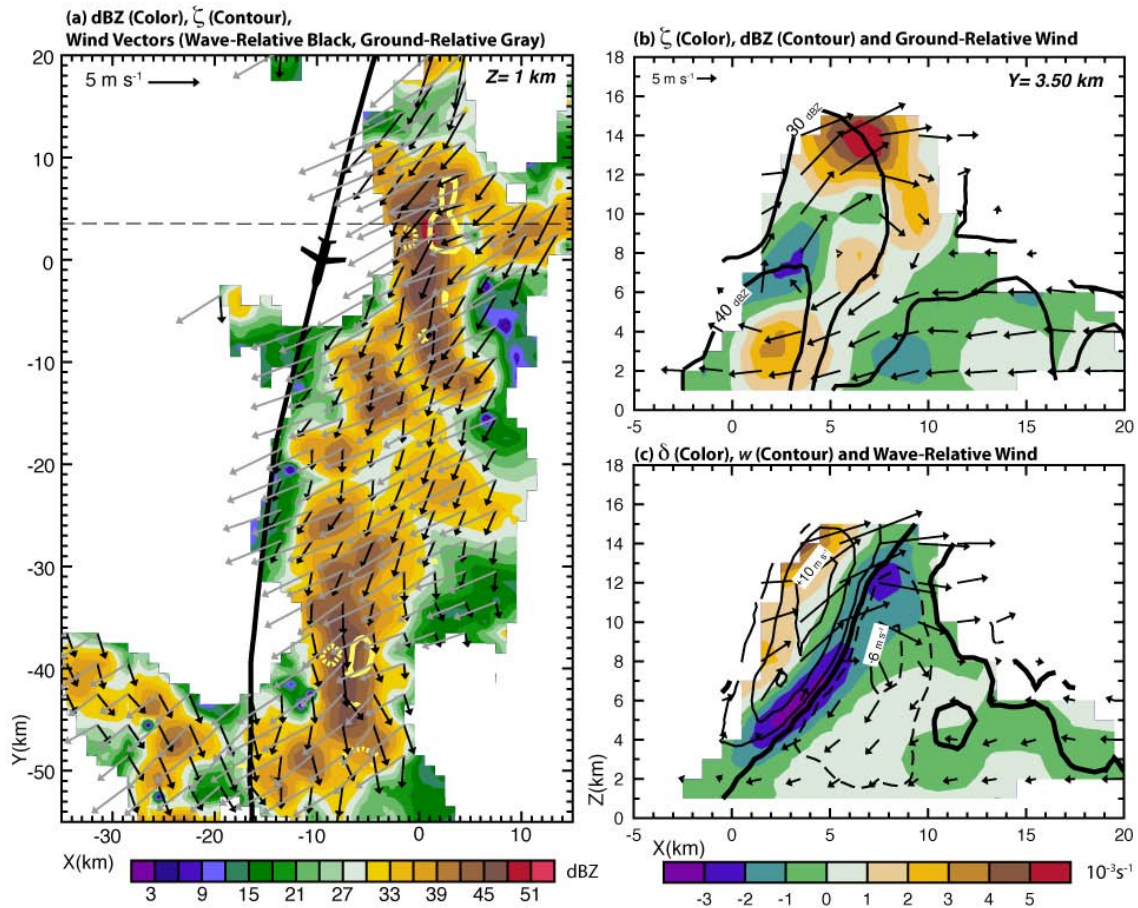


**Figure 3. NRL-P3 flight tracks and 850 hPa wave-relative dropsonde winds from TCS-08 research flights 11 (a) and 12 (b) in pre-depression Hagupit. Reference frame is translating zonally at  $4.5 \text{ m s}^{-1}$ . Dashed black track section in (a) corresponds to analysis area in Fig. 4.**

ELDORA radar analysis from TCS-08 indicates cyclonic vorticity-rich convective plumes (aka Vortical Hot Towers or VHTs) near the developing cyclonic low-level circulation, lending strong support to the “bottom-up” hypothesis for tropical cyclogenesis. Deep convective structures initiated near the center of the low-level circulation during the first mission provided a unique opportunity for several circumnavigations of a VHT in the pre-depression environment. An analysis of ELDORA data from the highlighted track section in Figure 3a near the convective burst region indicates a quasi-linear organization of multiple convective features (Fig. 4a). Earth-relative winds at 1 km altitude ( $\sim 900 \text{ hPa}$ ) show northeasterly flow (gray vectors), but in the co-moving frame reveal the northwestern side of the circulation (black vectors). Figure 4b shows a vertical slice through a deep, tilted structure in the convective line with 30 dBZ reflectivity reaching 15 km altitude (contours). This convective tower has strong vertical vorticity (color) that is primarily cyclonic and associated with an intense up/downdraft couplet seen in the velocity vectors. Wave-relative flow (Fig. 4c) more clearly illustrates the low-level convergence (color) at the leading edge of the convective structure that is tilting to the east with height.

Although further analysis is needed to understand the role of this convective line and subsequent bursts in Hagupit’s intensification, these preliminary results offer an encouraging look at how these observations are being used to evaluate the scientific hypotheses described above. Additional TCS08 analyses supported under this research grant include the data set from Super Typhoon Jangmi (2008): The analyses indicate the occurrence of significant gradient wind imbalance in the boundary layer and support the hypothesis that inner-core spinup occurs within the boundary layer. The results support also the hypothesis that VHTs are important elements in the storm spinup process. Observations and numerical simulations of the formation of typhoon Man Yi indicate that the “bottom-up” pathway was also favored within Man-yi’s critical layer. Finally, Tropical Rainfall Measurement Mission composite analyses of 55 developing easterly waves were used to study the spatial and temporal evolution of precipitation as genesis approaches. These analyses indicate that, as genesis neared: i) convection was favored in the Kelvin’s cat’s eye circulation; ii) the convective contribution to total rain rate became

dominant; iii) the radius of maximum convection decreased; iv) a convective-type heating profile was present. These findings add to the accumulating evidence for the “bottom-up” development pathway within easterly wave critical layers.



**Figure 4.** ELDORA analysis from 0036-0058 UTC 14 September, 2008. Panel (a) shows radar reflectivity (color, dBZ), and wind vectors in the ground-relative (gray) and wave-relative (black) frames at 1 km altitude. Yellow contours indicate vertical vorticity exceeding  $\pm 1 \times 10^{-3} s^{-1}$  (solid positive, dashed negative). The thick black line indicates the NRL P3 flight track and dashed gray line shows the location of the vertical slice in (b) and (c). Panel (b) shows reflectivity (10 dBz contours), relative vertical vorticity (color,  $10^{-3} s^{-1}$ ), and ground-relative wind vectors. Panel (c) shows vertical velocity (contour,  $m s^{-1}$ ), divergence (color,  $10^{-3} s^{-1}$ ), and wave-relative wind vectors.

## IMPACT / FUTURE WORK

The impact of this work is clear. It suggests that the ‘Marsupial Paradigm’ can be used to improve Naval Weather Forecasts in the Western Pacific region in cases for which an easterly wave disturbance can be tracked in observations and models. Our immediate next steps are to deepen our analysis of C-130 and NRL P3 Eldora data to evaluate the mesoscale processes occurring within the ‘mother pouch’ during the genesis sequence of Nuri and Hagupit. We will in particular use these analyses to assess the existence and role of VHTs in the tropical cyclogenesis process (Hendricks et al. 2004, Montgomery et



al. 2006). Several other non-developing cases were observed during the TCS08 field campaign and we plan to analyze these cases thoroughly as part of this research project. Additional TCS-08 flights during Hagupit's mature phase also present an opportunity to validate forecasts and test data assimilation techniques by incorporating research data into numerical models early in the tropical cyclone's lifecycle. Finally, the secondary eyewall formation observed in typhoon Sinlaku will be analyzed as part of the tropical cyclone structure change component of this research project. Formal publications will be prepared for all of these research topics as our research progresses and reaches maturity.

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#### **AWARDS RECEIVED DURING THIS GRANT PERIOD**

2008 Naval Postgraduate School, Graduate School of Engineering and Applied Sciences (GSEAS) Merit Award for Research: “For his fundamental contributions to the understanding of tropical cyclones, their formation, dynamics and prediction, and for his dedication to the mentoring of graduate students and young scientists in a collaborative environment”