

This discussion paper is/has been under review for the journal *Atmospheric Chemistry and Physics (ACP)*. Please refer to the corresponding final paper in *ACP* if available.

**The role of the
easterly wave critical
layer**

M. T. Montgomery et al.

The genesis of Typhoon Nuri as observed during the Tropical Cyclone Structure 2008 (TCS-08) field experiment – Part 1: The role of the easterly wave critical layer

M. T. Montgomery, L. L. Lussier III, R. W. Moore, and Z. Wang

Naval Postgraduate School, Monterey, California, USA

Received: 5 June 2009 – Accepted: 12 August 2009 – Published: 16 September 2009

Correspondence to: M. T. Montgomery (mtmontgo@nps.edu)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Abstract

An observational and real-time model forecast study of the genesis of Typhoon Nuri during the Tropical Cyclone Structure 2008 (TCS-08) field campaign in the western North Pacific sector is presented. Analysis and observational data show that the surrounding base state flow was an easterly trade wind flow and the precursor disturbance to Typhoon Nuri was an easterly wave that originated in the ITCZ in the Central Pacific and can be tracked more than 10 days prior to tropical storm formation. An overview of the field data is presented here using a newly proposed dynamical framework for tropical cyclone formation within the critical layer of an easterly wave. Despite propagating through a hostile environment ripe with strong vertical wind shear and relatively dry air, the easterly wave critical layer protected the proto-vortex and allowed it to gestate until it reached a more favorable environment. Within this protective “Kelvin’s cat’s eye flow” located within the wave’s critical layer existed a “sweet spot”, defined as the intersection between the wave trough and critical latitude, which was the preferred location for tropical cyclogenesis. Global Forecast System Final Analyses and IR satellite imagery, which shows convective bands wrapping around the sweet spot as genesis nears, confirm that this sweet spot is the location where Typhoon Nuri’s dominant low-level circulation emerges.

United States Air Force C130 and Naval Research Laboratory P3 research flights on 16 and 17 August collected flight-level, dropwindsonde, and Doppler radar data that allowed an evaluation of the dynamic and thermodynamic processes within the cat’s eye. The dropwindsonde analyses identified the precursor easterly wave disturbance on 16 August and identified an area of weak low-level cyclonic circulation on 17 August.

During the TCS-08 experiment “real-time forecasts” were produced in real-time using operational global prediction model data to support scientific missions. These forecasts were found to be useful in flight planning discussions and predicted Nuri’s genesis latitude within 1.5° 72 h in advance.

ACPD

9, 19159–19203, 2009

The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



1 Introduction

The western North Pacific region is the most active tropical cyclone basin on the earth, responsible for, on average, 26 of the 84 named storms annually (Neumann, 1993). Numerous synoptic-scale patterns have been identified as favorable to tropical cyclogenesis over the years, including, but not limited to: Tropical Upper Tropospheric Troughs (TUTT) (e.g., Sadler, 1976, 1978), formation within a monsoon trough regime (e.g., Holland, 1995) including the special cases of monsoon depression formation (Harr et al., 1996) and monsoon gyre formation (Lander, 1994), wave energy dispersion (Carr and Elsberry, 1995; Holland, 1995), filamentary intrusions from the subtropics (Deleon, 2008), mixed Rossby-gravity waves (Dickinson and Molinari, 2002), and easterly waves (Ritchie and Holland, 1999). Ritchie and Holland (1999) presented a climatology of formation mechanisms in this basin and documented five synoptic-scale regimes favorable to tropical cyclogenesis. Using eight years data from the Australian Bureau of Meteorology tropical analysis scheme, they attributed 42% of the western North Pacific tropical cyclogenesis cases to monsoon shear lines, 29% to monsoon confluent regions, 18% to easterly wave disturbances, 8% to wave energy dispersion, and 3% to monsoon gyre formation. Ritchie and Holland (1999) noted that these data most likely underestimate the true number of easterly wave type formations: “*development may also occur entirely in the easterly wave (18% of cases examined here) although the sample for this pattern most probably has a low bias due to the exclusion of genesis cases near the date line*”. Additionally, they noted: “*It is difficult to distinguish between genesis in the confluence region and genesis directly from an easterly wave because of the uncertainty of when genesis processes have finished*”. It is possible that the easterly wave pathway to genesis is more prominent in the western North Pacific basin than Ritchie and Holland (1999) suggested. Molinari et al. (2004) examined genesis cases in the western North Pacific basin and “*...believe that a significant fraction, and likely the majority, of western-Pacific tropical cyclones form in association with westward moving disturbances*”. Chen et al. (2008), for example, have proposed that

ACPD

9, 19159–19203, 2009

The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



80% of the tropical cyclone formations in this basin are due to easterly wave influences either directly or indirectly (through wave-gyre interactions)¹.

Although easterly waves are ubiquitous in the trade wind region of the tropics, typically only a small percentage of these waves develop into tropical cyclones (Frank, 1970; Ritchie and Holland, 1999). Recently, Dunkerton et al. (2009; hereafter DMW09) developed a new paradigm to describe the transition sequence from synoptic-scale easterly wave to tropical depression. Using the National Hurricane Center best track data, NASA-Tropical Rainfall Measurement Mission data, and European Center for Medium-range Weather Prediction Forecasts (ECMWF) Reanalysis (ERA-40) data during August and September (1998–2001), they examined tropical cyclone formation from monochromatic easterly waves in the Atlantic and Eastern Pacific basins and proposed a dynamical pathway to genesis that held true in 53/55 cases.

This proposed tropical cyclogenesis sequence is centered around three new hypotheses (hereafter H1–H3) describing the flow dynamics, moist thermodynamics, and wave/vortex interactions in which the Kelvin’s cat’s eye within the critical layer of a tropical easterly wave was shown to be the location of storm formation, observed near the intersection of the wave’s critical latitude and trough axis. The cat’s eye was hypothesized to be important to tropical storm formation because: H1) wave breaking or roll-up of the cyclonic vorticity near the critical surface in the lower troposphere provides a favorable environment for the aggregation of vorticity seedlings for TC formation; H2) the cat’s eye is a region of approximately closed Lagrangian circulation, and air is repeatedly moistened by convection and protected to some degree from dry air intrusion, which favors a predominantly convective type of heating profile; and H3) the

¹Chen et al. (2008) specifically use the phrase: “. . . monsoon gyres develop through a monsoon trough–easterly wave interaction”. However, their monsoon gyre definition is not consistent with the definition provided in the Glossary of Meteorology (2000). Despite this non-standard terminology, the wave-gyre interaction concepts that Chen et al. (2008) present may offer useful insight into the formation process in association with easterly waves in the western North Pacific and we would be remiss not to mention it.

The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



parent wave is maintained and possibly enhanced by diabatically amplified mesoscale vortices within the cat's eye. The entire sequence was likened by DMW09 to the development of a marsupial infant in its mother's pouch wherein the juvenile proto-vortex is carried along by the mother wave until it is strengthened into a self-sustaining entity.

DMW09 focused on the tropical waves over the Atlantic and Eastern Pacific sectors. The data collected during Tropical Cyclone Structure 2008 (TCS-08), a field campaign that took place from August–September 2008 over the western North Pacific, provided a unique opportunity to test the “marsupial paradigm” for easterly wave scenarios in a different basin. The overall objectives of TCS-08 were to develop a better understanding of storm-scale processes in the western North Pacific associated with tropical cyclones and to further the understanding of interactions between convective processes and tropical cyclone genesis, structure/evolution, intensity, and predictability (Elsberry and Harr, 2008). To accomplish these objectives, a multi-platform observing strategy was implemented. Both United States Air Force (USAF) C130 Hurricane Hunter aircraft [providing dropwindsondes, flight-level data, Stepped Frequency Microwave Radiometer (SFMR) data, and the ability to drop both Airborne Expendable Bathymetry Thermographs (AXBT) and ocean buoys] and the Naval Research Laboratory (NRL) P3 aircraft [fitted with the Electra Doppler Radar (ELDORA), dropwindsonde capability, a Doppler wind lidar, and the ability to collect flight-level data] flew aircraft research missions originating from Guam, a USA territory. For further information on the observing strategies and scientific objectives of TCS-08 see Elsberry and Harr (2008).

Typhoon Nuri was the first tropical cyclogenesis event occurring within aircraft observational range (~3000 km) during TCS-08. The storm was flown on four consecutive days (16–19 August) by the USAF C130, enabling the documentation of the evolution from easterly wave through Category 2 typhoon. The NRL P3 flew concurrently with the C130 on three days (16–18 August), enabling a documentation of the mesoscale and convective structure during the transition from easterly wave to tropical storm (TS) intensity.

The goal of this first study is to examine the genesis of Typhoon Nuri from the easterly

The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



5 wave precursor and provide a first test of the “marsupial paradigm” in the western North Pacific basin. This test is comprised of two parts: a post-analysis of a portion of the data collected during TCS-08; and an evaluation of the real-time marsupial forecasts for Typhoon Nuri that were produced and used as guidance for operational decisions during the TCS-08 field program.

10 The outline of the manuscript is as follows. Section 2 describes the data and methodology used. Section 3 examines the results obtained from analysis of the observational and forecast data. Section 4 discusses the genesis of Typhoon Nuri in the context of real-time forecasting. Section 5 summarizes the results presented in this paper and outlines our planned next steps for analysis of this storm.

2 Data and methodology

2.1 Data

15 Multiple datasets are used in this research: 1) Six-hourly GFS Final Analyses (GFS FNL) and forecast data, projected onto a one degree grid; 2) Multi-Functional Transport Satellite (MTSAT) half-hourly infrared (IR) satellite data at 4 km resolution; 3) Joint Typhoon Warning Center (JTWC) Best Track Data; 4) USAF C130 and NRL P3 drop-windsonde data; 5) Naval Oceanographic Global Analysis and Prediction System (NO-GAPS) analyses and forecast data; 6) QuikSCAT surface wind data; and 7) Cooperative Institute for Meteorological Satellite Services (CIMSS) satellite products. Not all of these data are independent. Specifically, the JTWC Best Track Data relied heavily on the MTSAT satellite imagery and aircraft observations for position fixes, and both numerical models assimilated the in-situ aircraft observations and satellite observations into their analyses.

The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



2.1.1 Summary of aircraft missions

Aircraft dropwindsonde data from the USAF C-130 and NRL P3 over two days (16–17 August) prior to TS declaration are evaluated herein. Figure 1 provides a summary of the key events in the genesis sequence of Typhoon Nuri. The USAF C130 operated at 31 000 ft to provide extensive vertical profiles of the atmosphere. Its primary missions were to provide synoptic and mesoscale analysis of the developing system, locate a developing circulation center, and direct the NRL P3 to mesoscale areas of interest. The primary mission of the NRL P3 was to use the ELDORA to sample the convection within the marsupial “pouch” of the parent wave disturbance, with secondary missions of providing dropwindsonde and flight-level data coverage. While on station, the NRL P3 typically flew at altitudes of 8 000–12 000 ft.

During the 16 August flight, the USAF C130 flew in a “lawn mower” pattern, centered on 147E, and oriented along the axis of the easterly wave trough. Deviations were made to the pattern during flight to better sample the western edge of the wave as it was propagating faster than forecast and to the southern edge of the wave where the convection was most vigorous. The second C130 mission (17 August) flew a square spiral pattern centered at 14 N, 142 E, the intersection of the wave trough and the critical latitude (i.e., the “sweet spot”) derived from NOGAPS model forecast data. In-flight deviations were made to this pattern as a low-level circulation was identified by dropwindsonde data in the southwestern corner of the pattern.

The first NRL P3 flight (16 August) focused on the convective process occurring near the potential “sweet spot” as identified by the NOGAPS forecast. Toward the end of its mission, the aircraft climbed to flight levels greater than 20 000 ft to provide dropwindsonde coverage on the extreme western edge of the wave, which was not covered by the C130. The second NRL P3 flight (17 August) began as a rectangular pattern within the square spiral of the USAF C130 pattern. Its mission was to provide a statistical sample of the convection within the “pouch”, therefore, multiple passes on convective cells were not made in order to obtain an unbiased sample.

The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



2.2 Analysis Methodology

Marsupial analysis and forecast products were produced using the following methodology:

2.2.1 GFS FNL

5 For GFS FNL analyses, the maximum latitudinally-averaged (9–17 N) total precipitable water (TPW) was used for both wave tracking and to calculate wave phase speeds. This methodology has three significant advantages: i) it allows tracking of moisture in two dimensions, rather than simply the moisture at the latitude of the “sweet spot”;
10 ii) it results in a stronger “pouch” signal if there is not strictly westward translation; and
15 iii) it allows for wave tracking when the moisture gradient was not as obvious, such as in the relatively moist region of the western North Pacific. Disadvantages of this methodology are evident when the “pouch” and/or the distribution of moisture within are not symmetric or the wave is relatively dry. This situation results in a weaker TPW signature since the potential for dry air on the outskirts of the “pouch” tends to be included in this average value. For the Nuri case, the advantages of the latitudinal averaging outweighed these disadvantages.

Once the zonal phase speeds were calculated, a streamline analysis in the co-moving frame was produced. The critical latitude is defined as the latitude at which zonal velocity equals the zonal phase speed, i.e., $u=C$; the trough axis is defined as
20 the locus for which the meridional velocity vanishes, i.e., $v=0$ and the relative vorticity is cyclonic (DMW09 and Wang et al., 2009; hereafter WMD09). The intersection of the critical latitude and the trough axis pinpoints the sweet spot.

2.2.2 Real-time marsupial forecasts

25 WMD09 demonstrated that the preferred location for tropical cyclogenesis could be predicted within 200 km up to 72 h in advance using operational numerical models. For

The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



GFS and NOGAPS marsupial forecasts produced during TCS-08, an average phase speed was derived from Hovmoller diagrams using three meteorological variables to minimize errors arising from individual tracking methods: i) a zonal phase speed was calculated using the zero contour line in the meridional wind field. For real-time forecasts with no filtering, the wave signal in the meridional wind field is noisier because of high frequency variations and/or short-lived mesoscale vortices within the “pouch” (WMD09). ii) A phase speed based on local fluid rotation was calculated using either relative vorticity or Okubo-Weiss (OW) as defined in DMW09 ($OW = \zeta^2 - S_1^2 - S_2^2$); where ζ is relative vorticity, S_1 is the stretching deformation, and S_2 is the shearing deformation. This has limitations in the cases of tracking weak waves where the rotational signature has yet to strengthen. iii) A phase speed based on the tracking of a zonal moisture gradient: TPW for GFS and relative humidity for NOGAPS (WMD09). The TPW signature was observed to be one of the stronger pouch tracking methodologies in the Atlantic (WMD09); however, the signal is much weaker in the western North Pacific basin as much of this region is continuously moist and not as vulnerable to outbreaks from the Saharan Air Layer.

Diagnostic output of pertinent field variables was presented as vertical cross-sections after averaging each variable horizontally within a $3^\circ \times 3^\circ$ box centered on the “sweet spot” (Montgomery et al., 2009; Wang et al., 2009b). These diagnostics were considered as an approximate representation of the pouch evolution. Examples of variables used in vertical cross-sections include relative vorticity, OW, and detrained volume flux (Δ), which was calculated at each level according to:

$$\int_A \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right) dA \quad (1)$$

where u denotes zonal velocity, v the meridional velocity and dA is the horizontal area element (Raymond et al., 1998).

The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



3 Results

3.1 Evolution of the easterly wave precursor (12Z 7 August–00Z 10 August)

Although the ultimate origin of the pre-typhoon Nuri disturbance is beyond the scope of this paper, the CIMMS morphed TPW analysis (not shown) suggests it may have originated from a “roll-up” episode in the Central Pacific Inter-tropical Convergence Zone (ITCZ) on 12Z 7 August. At this time the GFS FNL first identified a low-level² southwest-northeast tilted easterly wave in the streamline analysis centered at 8N, 165E. The vorticity and moisture fields associated with the easterly wave are disorganized. Whether this roll-up was caused by an underlying hydrodynamic instability of the ITCZ (Ferreira and Schubert, 1997; Wang and Magnusdottir, 2006) or a non-linear evolution of a nearly-neutral moist Rossby wave/vortex on the northern side of the ITCZ (DMW09) is unknown and beyond the scope of the current investigation. For the purposes of this study, we accept the existence of this finite-amplitude wave/vortex structure that can be tracked westward for ten days prior to the declaration of Tropical Storm Nuri.

Figure 2 depicts a GFS FNL Hovmoller diagram of latitudinally-averaged TPW valid from 00Z 6 August until 12Z 17 August. A wave signal (indicated by a region of higher TPW) is first evident in these data at 00Z 8 August. This signal may be tracked coherently in this TPW Hovmoller from this time until the TS stage is declared by the JTWC forecasters (12Z 17 August). Due to the extended period that this wave can be tracked, the wave is not expected to maintain a constant phase speed throughout its lifecycle. Observed changes in propagation speed can be attributed to synoptic-scale regime changes or variations in the vertical level of the maximum amplitude of the

²For the analyses presented in this paper, low-level refers to levels below 850 hPa. The maximum amplitude of the easterly waves observed during TCS-08 was usually lower than what is typically observed in the Atlantic sector. This is consistent with Reed and Recker (1971) and Chang et al.’s (1970) findings, and is the primary reason why we present analyses at levels below 850 hPa rather than the original DMW09 methodology.

The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



wave over time. Two distinct regimes are identified here and a zonal phase speed for each is calculated using the GFS FNL TPW Hovmoller diagrams. The first time period lasts from 12 Z 7 August–00 Z 11 August and is accompanied by a higher zonal phase speed (10.5 m s^{-1}). As the wave crossed the dateline, it entered a region of weaker synoptic-scale steering flow, which caused the phase speed of the wave to gradually decrease. The average wave phase speed over the later period (06 Z 11 August–12 Z 17 August) is 6.96 m s^{-1} .

These phase speeds have been used with the GFS FNL to construct an “official” track of the “sweet spot” associated with the easterly wave that formed Typhoon Nuri. Figure 3 displays the location of the “sweet spot” (solid blue triangles) at the 925 hPa level at 12 h intervals from 12 Z 7 August–12 Z 17 August, together with the JTWC Best Track position beginning at 00 Z 16 August (red symbols). While the initial “sweet spot” of the wave trough was at approximately 10 N, it propagated steadily westward and gradually northward, remaining between 14.5–17 N from 14 August onward. The slight southerly movement on 16 August is believed to be a response to the strong convective activity observed by both satellite and aircraft radar data in the southern quadrant of the “pouch”.

During the early evolution of this disturbance, a closed low-level cyclonic circulation was evident in the co-moving frame from 00 Z 8 August until 00 Z 12 August. Values of OW within the “pouch” steadily increased (not shown) prior to the wave crossing the dateline (00 Z 10 August). This is indicative of the disturbance showing favorable characteristics for tropical cyclogenesis (consistent with WMD09). Adverse environmental conditions during 10–14 August (discussed below) are argued to prevent genesis during this time.

3.2 Maintenance of the “pouch” through a hostile environment (12 Z 10 August–00 Z 15 August)

Gray (1968, 1975) introduced a set of necessary conditions for tropical cyclogenesis that remain generally accepted today. Here, they are summarized into the following

The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



four conditions: i) sea-surface temperatures $>26^{\circ}\text{C}$; ii) weak 850–200 hPa vertical wind shear; iii) sufficient cyclonic vorticity in the lower troposphere; and iv) moist convective instability and a moist mid-troposphere. This section will focus on the period from 12 Z 10 August–00 Z 15 August, a time when these favorable conditions generally were not satisfied. It will be suggested that this hostile synoptic environment had a profound influence on the evolution of the pre-Nuri disturbance.

As the pouch crossed the dateline, its translation takes on a northerly component, which results in a displacement of the “sweet spot” from 10 to 15 N over the next five days. Concomitantly, the “pouch” entered a region with relatively dry low-mid level air and strong vertical wind shear, conditions that are widely accepted to be particularly hostile to tropical cyclone formation. Figure 4 displays a times series of the CIMMS Morphed TPW product valid at 12 Z each day over a four-day period (9–12 August). The first panel shows the moist “pouch” of the pre-Nuri disturbance as an area of higher TPW centered at 10 N, 175 W on 9 August. This relatively moist “pouch” was: i) surrounded on three sides by drier air, with only the air to the south through southeast being moist (consistent with DMW09), and ii) disconnected from the moist air in the western North Pacific. The pouch signal (identified as the area of relatively higher moisture) is more evident 24 h later (10 August) when the pre-Nuri “pouch” (11 N, 177 E) takes on the shape of an elongated oval of higher moisture and relatively drier air remains to the north through west and south quadrants upstream of the “pouch”.

On 11 August (Fig. 4), the moist air associated with the “pouch” (12 N, 172 E) has propagated west and has begun to link with the moist air in the western North Pacific. There remains an area of relatively drier air separating this feature from the main pool of western North Pacific moisture. Furthermore, the “pouch” continues to exhibit higher TPW than its surrounding environment and the TPW within the pouch has increased over time. This supports DMW09’s second hypothesis (H2) that the marsupial “pouch” tends to protect the seedling embryo from the lateral intrusion of dry air. By 12 August (Fig. 4), the moist “pouch” has almost entirely merged with the western North Pacific moisture pool. The moisture content within the “pouch” (12 N, 162 E) remains higher

The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



than the ambient environmental moisture. A small amount of relatively drier air remains to the west, still separated from this moist air-mass feature.

One factor inhibiting tropical cyclogenesis during this time period is the strong vertical wind shear. Figure 5 shows a six panel time series of deep layer (200–850 hPa) shear and 925 hPa streamlines in the co-moving frame from the GFS FNL valid at 12 Z each day from 10–15 August (the solid blue triangle indicates the position of the “sweet spot”). On 10 August, a closed low-level cyclonic circulation has just crossed the date-line and is entering an unfavorable area shear of deep layer vertical shear greater than 40 kt. Over the next 24 h, the areal extent of the strongest vertical wind shear (>40 kt) decreases and shifts to an area between 160–170 E and 12–18 N. This strong vertical shear is believed to have contributed to the weakening circulation observed on 11–12 August. By 12Z 12 August, the closed circulation in the co-moving frame is no longer evident. During the next two days (13–14 August), the area of strongest shear (>40 kt) is observed to retreat eastward and, as a result, the precursor disturbance encounters a less hostile environment. After 12Z 14 August, the pouch of the pretyphoon Nuri disturbance enters and remains in a region of 5–10 kt of vertical shear until genesis.

During the time period 9–13 August the wave’s presence in an area of low hurricane heat content (HHC)³ was an inhibiting factor to the development of deep convection and tropical cyclogenesis. Figure 6 shows the NRL Stennis HHC analysis for 12Z 15 August with the “sweet spot” track overlaid (solid blue triangles). As oceanic heat properties evolve slowly (time scale of weeks to months), this figure is representative of conditions over this time period. The motion of the “pouch” from 10–13 August

³The NRL HHC plots use the definition presented in Leipper and Volgenau (1972), who define HHC as the integrated heat content down to the 26°C isotherm relative to water of 26°C: $HHC = \rho C_p \Delta T \Delta Z$ for $z < Z_{26}$. Here ρ is the density of ocean water near the mixed layer region, C_p is the specific heat of ocean water at constant pressure near the mixed layer region, ΔT is the average temperature difference above 26°C for a given depth increment, and ΔZ is the incremental depth.

The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



places it over an area of lower HHC, which tends to reduce the convective available potential energy. The result is a somewhat reduced temperature of the boundary layer air, which in turn tends to effectively stabilize the lower troposphere and thereby inhibit deep convection. This is known to be unfavorable for tropical cyclogenesis. After 12 Z 14 August, the wave pouch moves into a region of higher HHC, which is favorable for tropical cyclogenesis.

3.3 Reinvigoration of convection and initiation of the genesis sequence (12Z 15 August – 12Z 17 August)

Figure 7 depicts a times series of 925 hPa streamlines from the GFS FNL in the resting frame valid at 12 h intervals from 12Z 15 August–12Z 17 August. Figure 8 shows the corresponding time series in the co-moving frame. Overlaid on these figures are MTSAT IR brightness temperature data and the JTWC Best Track position (black circle). The images in the co-moving frame show the wave trough axis (black line) and critical latitude (purple line). The thick black line is the approximate track of the “sweet spot” center. On 12Z 15 August, strong convection begins to form on the eastern and southern portions of the wave trough (Fig. 7, when viewed in the resting frame) or “pouch” (Fig. 8, when viewed in the co-moving frame) as it has moved into an environment of low vertical wind shear (Fig. 5) and higher HHC (Fig. 6). A closed low-level cyclonic circulation is evident in the co-moving frame. Interestingly, this is not evident in the ground-based reference frame and is consistent with DMW09 who noted that a closed circulation could be found in the co-moving frame up to 72 h earlier than in the ground-based reference frame.

The second panels of Figs. 7 and 8 are valid during the first joint USAF C130/NRL P3 flights into the pre-Nuri disturbance (00Z 16 August, see Fig. 1). The intersection of the critical latitude and wave trough is at 14.9N, 145.3E. The strongest convection at this time is located to the south and east of the “sweet spot”, but it remains largely within the “pouch”. This is consistent with DMW09, who argued that repeated convection within the pouch leads to continued moistening, favoring further deep convection, resulting

The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



in an important positive feedback process. The southern and eastern portions of the “pouch” were the favored regions for convection at this time, most likely because of their location in an area of higher HHC.

The C130/P3 research missions centered on 00 Z 16 August sampled the horizontal extent of the “pouch”. Figure 9 depicts the dropwindsonde data from these flights overlaid with MTSAT IR data. The top panel represents 850 hPa wind barbs in the resting frame and the bottom panel shows the data in the co-moving frame. The red cross is the location of Guam. The blue triangle indicates the approximate location of the dropwindsonde-derived closed low-level cyclonic circulation in the co-moving frame. 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. In the co-moving frame, the dropwindsonde data (Fig. 9) 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.

The GFS FNL/MTSAT analysis valid at 12 Z 16 August (middle panels, Figs. 7 and 8) depicts a closed low-level cyclonic circulation in both reference frames. However, the center of this cyclonic circulation in the resting frame is located more than one-degree south than in the co-moving frame. Figure 10 is a zoomed-in view of this time period; strong convection has now begun to occupy all quadrants of the “pouch” and is beginning to become centered on the “sweet spot”. Of particular interest is the initiation of convective bands to the south and northeast of the “sweet spot” (red arrows), which satellite loops show to spiral cyclonically inward towards the center of the circulation in the co-moving frame. At the time of the second joint USAF C130/NRL P3 sortie into the pre-Nuri disturbance (00 Z 17 August), convection has filled all quadrants of the “pouch” and the banding seen 12 h earlier is now even more evident (Figs. 7 and 8). These observations suggest that deep convection is beginning to wrap around the low-level cyclonic circulation center in the co-moving frame as the system is undergoing tropical cyclogenesis (JTWC upgraded this invest area to a TD prior to this time, Fig. 1).

The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The second C130 flight identified a broad cyclonic circulation center at 850 hPa in the southwestern portion of the flight pattern at approximately 14 N, 139.5 E (Fig. 11). This circulation center was observed to tilt with height and was weak and shallow. The area where this cyclonic circulation was observed was concurrent with the areas of strongest convection (Fig. 7) and was consistent with the closed low-level cyclonic circulation in the GFS FNL resting-frame analysis (Fig. 7). In the co-moving frame, however, the low-level cyclonic circulation is slightly farther east (140.5 E) and north (15 N) of the circulation center in the resting frame. In this co-moving frame, the circulation is well defined and more robust than the weakly observed circulation in the resting frame. This suggests that the flow pattern in the co-moving frame is more representative of the intrinsic atmospheric state (developing TD) than the chaotic flow observed in the resting frame.

3.4 Consideration of other possible factors in the formation of Typhoon Nuri

3.4.1 The possible role of a monsoon trough

In the case of Typhoon Nuri, the presence of equatorial westerlies near Palau (7 N, 134 E) has been cited by some as evidence of the presence of a monsoon trough leading to the genesis of this easterly wave (versus the non-development of previous easterly waves observed during TCS-08). The following analyses show that the westerly flow near Palau: i) was not indicative of the presence/formation of a monsoon trough; and ii) had no discernible impact on the formation of Typhoon Nuri.

Analysis of skew-t data (not shown) shows weak westerly flow (5–15 kt) in the lower troposphere at Koror, Palau from 00 Z 14 August–00 Z 16 August. During this time period, the “sweet spot” of the pre-typhoon Nuri disturbance is centered between 14.9–16.2 N and moves from 152.8–145.3 E. Therefore, the Guam sounding (13.8 N, 144.5 E) is more representative of the conditions influencing the formation of Typhoon Nuri. These data (not shown) indicate deep easterly flow throughout the depth of the troposphere until 00 Z 15 August. After this period, a classical easterly wave signature

The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



is evident in the Guam sounding (which was corroborated by aircraft data) as low-level winds shift from NE-E-SE during 12Z 15 August–00Z 17 August. At no point did the Guam sounding data indicate the presence of low-level westerly flow extending into this region.

5 These data are corroborated by the spatial evolution of the observed wind field in both satellite-derived cloud-drift winds and QuickSCAT data. We have argued that 12Z 15 August is a critical time in the tropical cyclogenesis sequence of Typhoon Nuri, as this coincides with the reintensification of convection within the marsupial “pouch”. The CIMSS low-level cloud drift winds prior to this time at 06Z 15 August (Fig. 12 top) and QuickSCAT surface wind data (Fig. 12 bottom) valid 15 August both show approximately uniform easterly flow from the dateline to points well west of 140 E and north of 9 N (the solid red line demarcates the transition between easterly flow and westerly flow)⁴. The westerly winds near Palau do not extend farther than 138 E. This confirms that large-scale westerly winds were not present in the area of the pre-Nuri disturbance (indicated by the red circle in Fig. 12); nor did they play any discernible role in the genesis of Typhoon Nuri. Examination of the CIMSS data for the period 10 00Z/14–18Z/16 August (when JTWC upgraded the disturbance to a TD) confirms that synoptic-scale westerly flow was not observed farther east than 138 E (below 20 N) and corroborates the lack of a monsoonal flow in the vicinity of the pre-Nuri disturbance. On 15 16 August both the QuickSCAT surface winds and GFS FNL data indicate the presence of isolated westerlies near the southeast portion of the wave in the resting frame. We suggest this is evidence of the wave forming a closed cyclonic circulation at the lower levels, rather than a large-scale, organized monsoon flow.

⁴The QuickSCAT data shows a small area of isolated westerly winds located between 148 E 8–9 N on 15 August. These westerlies are spatially separated from the large-scale westerlies that extend through the Philippine Sea and northward. These westerly winds at 148 E 8–9 N are potentially signs of cross-equatorial flow extending into the developing low-level cyclonic circulation. They are not evidence of monsoonal flow impacting the genesis of Typhoon Nuri, as the flow is too limited in horizontal scale and not evident in the analysis prior to this time.

The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



3.4.2 The possible role of a TUTT

The presence of TUTT cells will next be argued to have no impact on the genesis of Typhoon Nuri. Two upper-level cyclonic circulations were identified by the CIMMS upper level cloud drift winds (not shown) in the general region of pre-Nuri disturbance. The first is a weak, nearly stationary cyclonic circulation at 15 N, 160 E present from 01 Z 14 August–21 Z 14 August. After this time, this circulation center drifts slightly south to 11 N and is present until 06 Z 15 August. Subsequently, it is no longer distinguishable, as weak convection was initiated in the area. The second is a stronger upper-level cyclonic circulation that entered the western North Pacific (28 N, 175 E) on 12 Z 15 August. This TUTT moved southwest, eventually reaching 24 N, 168 E by 00 Z 17 August. However, these upper-level cyclonic circulations observed in the CIMMS data are not believed responsible for the genesis of Typhoon Nuri. The first TUTT circulation was too weak and became indistinguishable as the genesis process began. The second TUTT, which would represent a much better fit to Sadler's (1976, 1978) classical definition, was too far removed (approximately 19°) from the genesis region to have any significant dynamical or thermodynamical influence on the pre-Nuri disturbance.

3.5 Evaluation of real-time forecasts (00 Z 11 August–12 Z 17 August)

The construction of real-time forecasts incorporated in the methodology outlined in WMD09 was applied successfully during the TCS-08 field experiment in order to provide forecast guidance for operational flight planning. This methodology is based on the assumption that, while global forecast models currently are unable to represent the mesoscale processes in tropical cyclogenesis, they often do an adequate job capturing the synoptic scale evolution. In the context of the marsupial paradigm, this suggests it is possible to track the easterly wave's critical layer and, moreover, predict the preferred location for tropical cyclogenesis to occur (WMD09), even in instances where tropical cyclogenesis is not predicted by the model. It is in this context that real-time "marsupial forecasts" can provide very useful information for the forecasting of tropical

The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



cyclogenesis.

Figure 13 depicts an example of the T+72 h NOGAPS (initial time: 12Z 14 August) “marsupial forecast” valid at 12Z 17 August (when the pre-Nuri disturbance was upgraded to a TS by JTWC). The left panel displays 925 hPa streamlines in the co-moving frame along with OW, the critical latitude, and trough axis. The location of Guam is indicated by the red plus sign. The right hand side depicts vertical cross-sections of pouch diagnostics for OW, relative vorticity, and detrained volume flux. This forecast was used in the 15 August Daily Planning Meeting to make a go/no go decision for reconnaissance flights and was a significant factor in the decision to fly this disturbance.

At this forecast hour, all of the four global models used during TCS-08 (NOGAPS, GFS, ECMWF, UKMET) depicted an easterly wave moving through the region (not shown). However, none developed the wave into a closed circulation in the earth-relative frame or a tropical cyclone at any validation time. The marsupial forecast product shown depicts a closed low-level cyclonic circulation (in the co-moving frame) along with a strong area of OW surrounding the “sweet spot”. This “marsupial forecast” predicted the favored region for genesis, should it occur, within 1.5° latitude of the JTWC Best Track position⁵.

The model diagnostics (Fig. 13) predict low-level convergence around the genesis time, leading to an enhancement of low-to-mid-level relative vorticity. The OW/relative vorticity plot shows an increase in both variables in the lower levels; variations in the two are qualitatively similar in the vertical (especially in the lower troposphere). This suggests that almost all of the vorticity being produced is from the curvature vorticity

⁵We have shown that operational numerical prediction models have the capability to predict genesis *location* in an operational environment using “marsupial analysis methods”. Although the success of these “marsupial forecasts” is dependent on the forecast skill of the global model, the diagnosis based on the “marsupial paradigm” provides additional insights to the standard model forecast. In the Nuri case, operational models did well in forecasting the favored latitude for genesis. However, the error in longitude was approximately 4° for the 72 h NOGAPS forecast, primarily due to the model’s inaccurate representation of the propagation of the parent easterly wave (due to errors in representing the background easterly flow).

The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



(in the co-moving frame), a favorable feature for tropical cyclogenesis (DMW09).

We believe that these “pouch” diagnostics have the potential to assist operational forecasters in easterly trade wind regimes because they offer the advantages of: i) a wave-centric viewpoint for diagnostic analyses; and ii) centering intense observations or satellite positioning around the preferred genesis location.

4 Interpretive discussion

JTWC began tracking the pre-Nuri disturbance at 00 Z 16 August with an initial center position of 146.8 E, 13.2 N (Fig. 3), and it was classified as DB (depression beginning). At this time, the intersection of the GFS FNL⁶ 925 hPa critical latitude and wave trough axis was located at 145.3 E, 14.9 N. Twenty-four hours later, JTWC upgraded the developing storm to a TD centered at 140.2 E, 14.8 N, while the “sweet spot” was located at 139.7 E, 15.9 N. Finally, at 12 Z 17 August 2008, JTWC upgraded the TD to a TS located at 136.7 E, 16.1 N while the “sweet spot” was at 136.8 E 16.3 N. Of particular interest to this study is the abrupt shift north in the JTWC Best Track between 00 Z and 06 Z 17 August. According to JTWC, the center of the developing TD shifts from 14.8 N to 16 N in the span of six hours, whereas it had shifted only 1.6 degrees north over the previous 36 h. Furthermore, the position of the “sweet spot” varied by only 1.8 degrees in 36 h and remains well north of the JTWC Best Track position until TS declaration. These facts motivate the following question: Is this evidence of a sudden northward propagation of this disturbance, or a potential tracking error in the best track data?

⁶While there are limitations to the GFS FNL (data assimilation, resolution, etc.) it is incorporated in this analysis due to the limited amount of observational data available in the western North Pacific. The GFS FNL is generally in good agreement when verified against observations. Furthermore, operational ECMWF and NOGAPS analyses provide a consistent evolutionary picture of the easterly wave and vorticity field from 7 August until genesis, which are also similar to the GFS FNL. This gives us confidence that that GFS FNL is representative of the synoptic-scale conditions leading up to the genesis of Typhoon Nuri.

The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



As discussed in Sect. 3, on 00 Z 16 August (Fig. 8), the strongest convection associated with the pre-Nuri disturbance was located within the southern (and to a lesser extent the eastern) quadrant of the “pouch”. Figure 14 displays the GFS FNL from this time with 925 hPa streamlines in the co-moving frame, OW (shaded), the wave trough axis (thick black line), critical latitude (purple line), and JTWC Best Track position (black circle). These data are consistent with satellite observations in that the OW maximum (and by proxy, the strongest vorticity and low-level convergence) is located in the southern portion of the “pouch”. With limited conceptual models and guidance on locating the center of a developing typhoon, declaring its position in the middle of the strongest convection and vorticity maximum is understandable⁷. However, deep tropical convection is generally chaotic and unpredictable (Nguyen et al., 2008). Furthermore, maxima in vorticity do not necessarily coincide with the emerging circulation center and small vorticity anomalies may be present throughout the pouch (Montgomery et al., 2009; Wang et al., 2009b).

By 12 Z 16 August the GFS FNL (Fig. 14) data shows an increase in the aerial coverage of OW, as the higher OW values are now observed throughout most of the “pouch”. While the OW maximum remains in the southern quadrant, it has advected closer to the “sweet spot”. At this time, the IR data shows evidence of banded structures beginning to wrap around the “sweet spot” (red arrows in Fig. 10)⁸. When viewing this sequence in the resting frame (Fig. 10), the cyclonic circulation is farther south (12.5 N). The cloud features observed in the IR data appear to be a mass of convection primarily to the northwest of this center, rather than convective bands wrapping into a seedling tropical cyclone. Although this difference is subtle, it is important and provides evidence that

⁷Although typhoon reconnaissance flights are typically not available in the western North Pacific, the JTWC Best Track data was influenced by the aircraft missions flown during TCS-08, as the potential low-level cyclonic circulations identified by the USAF C130 were incorporated into their best track determinations.

⁸While perhaps not transparent in the static images shown, satellite loops depict banded structures spiraling cyclonically inward toward the “sweet spot”.

the preferred region for genesis was the “sweet spot” at the northern portion of the wave, rather than the southern circulation. DMW09 suggested that the high frequency of storm formation occurred at or near the center of the translating gyre in almost all of the Atlantic cases they studied: “. . . seems almost uncanny and suggests to our minds an invisible ‘guiding hand’ from synoptic and meso- α scales”. The so-called “guiding hand” principle is summarized therein:

“. . . whereas upscale aggregation of vorticity and its amplification by deep convection are essential to TC formation, they are not entirely responsible for the formation of a closed tropical depression in the first place. This formation is at least partly due to the dynamics of moist waves and involves a direct enstrophy cascade from larger synoptic-scale disturbances to mesoscale vorticity anomalies. This argument rests on the coherent relationship observed between the critical layers of tropical waves and tropical cyclogenesis events occurring in such regions”.

Our initial analysis of the observational data in the Typhoon Nuri case suggests that this “guiding hand” principle was indeed at work. In Part 2 of this paper we will evaluate these concepts further through analysis of the mesoscale processes occurring within the “pouch” during Typhoon Nuri’s genesis sequence.

AT 00 Z 17 August, the convection is more evenly distributed throughout the “pouch” (Fig. 8) and there is a significant area of banded convection to the northeast, wrapping around into the “sweet spot”. The GFS FNL OW maximum has increased in aerial extent and intensity, and has organized around the center of the “sweet spot” (Fig. 14). At this point the JTWC Best Track position has the center at 14.8 N (Fig. 14), which appears to be close to the location of the strongest convection. However, it remains well south of the “sweet spot” and the OW maximum. By 12 Z 17 August (the time JTWC upgraded the disturbance to a TS) both centers are almost identical (Fig. 14). The OW has increased over the last 24 h, consistent with the evolution seen in WMD09.

The evolution of convection described above is consistent with high-resolution idealized numerical simulations performed by Montgomery et al. (2009) depicting the transition of an easterly wave critical layer to a tropical depression. Figure 15 portrays an

The role of the easterly wave critical layer

M. T. Montgomery et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

84 h time series of surface precipitation (explicitly resolved on the 3 km grid), 850 hPa streamlines in the co-moving frame, the wave trough (black line), and critical latitude (purple line). For a complete description of the model set-up, initial conditions, and physics, see Montgomery et al. (2009). The first three panels of this time series (120–144 h) depict light unorganized precipitation in all quadrants of the “pouch” with a maximum to the northeast (akin to the unorganized convection seen in the pre-Nuri disturbance prior to 12 Z 16 August). By the 156 h time period, the precipitation structures are beginning to organize and banding features emerge. The 166 h time period shows organized bands wrapping around the “sweet spot”. The next three periods (180–204 h) show these banded structures spiraling into the “sweet spot”, an increase in the intensity of the precipitation, and heavy precipitation moving closer to the center and filling all quadrants of the “pouch”. The evolution of the model-simulated precipitation is similar to that observed in Nuri in the sense that convection is sustained and enhanced near the center of the “pouch”.

On the basis of the evidence presented, these data strongly suggest that: i) the dynamical genesis sequence proposed by DMW09 can be useful for understanding the evolution of easterly waves in the western North Pacific basin. The juxtaposition of the closed cyclonic circulation in the co-moving frame and “sweet spot” in the GFS FNL is consistently farther north and shows a less abrupt shift than the center positions issued by JTWC. The evolution of banded features in the IR data and evolution of OW in GFS FNL strongly support the viewpoint that following this northern center is the simplest and superior way to track the pre-Nuri disturbance. ii) Deep convection alone should not be relied upon to identify the center of a developing tropical cyclone because deep convection is inherently chaotic and has been shown elsewhere to be an unreliable indicator of genesis location (DMW09). While OW and/or vorticity at the 850 hPa level may be more robust, neither is as good as streamline (or streamfunction) analysis, which is superior for resolving the potential genesis location as shown by DMW09 and confirmed in this case. iii) Using the “sweet spot” model to track potential genesis locations should be a useful tool for identifying low-level cyclonic circulation centers

The role of the easterly wave critical layer

M. T. Montgomery et al.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

operationally in the early genesis stages and may ultimately prove superior to methods being currently employed.

5 Conclusions and future work

This paper has presented a first analysis of the tropical cyclogenesis of Typhoon Nuri that occurred in the western North Pacific basin during the TCS-08 field campaign. The basic state flow within which Typhoon Nuri formed was an easterly trade-like flow and the progenitor disturbance was an easterly wave that propagated approximately zonally over a ten-day interval with an earth-based zonal phase speed varying between 10 m s^{-1} and 6.96 m s^{-1} . Given the easterly wave character of this formation event it was considered a viable candidate for the “marsupial paradigm” proposed recently by DMW09. Observational evidence has been presented to support hypotheses H1–H3 of DMW09 for this Nuri case.

The following factors provide observational support of H1 in the tropical cyclogenesis sequence of Typhoon Nuri: i) convection, despite beginning in the southern quadrant of the “pouch”, remained largely within the “pouch” and became organized around the “sweet spot” as genesis neared. IR satellite imagery shows the beginning of banded convection around this location on 12Z 16 August. ii) The dominant circulation that emerged as Typhoon Nuri was located within the highly vortical region of the wave’s cat’s eye near the intersection of the wave trough and the critical latitude (confirmed by GFS FNL and IR satellite data).

Similarly, in the case of H2: i) the GFS FNL identified a set of closed streamlines in a translating frame of reference representing the “pouch”. This pouch was evident approximately nine days prior to formation. The ‘pouch’ significantly weakened as it traversed through a hostile environment, and then re-emerged as a coherent circulation two days prior to TS declaration. ii) The reinvigoration of convection at 12Z 15 August occurred largely within the “pouch” and we suggest was most likely triggered by an area of higher HHC and vorticity located in the southern quadrant of the “pouch”. Over

The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



the next 36 h, the deep convection became more vigorous and the CIMMS TPW analysis suggests continual moistening of the column. iii) CIMMS TPW analyses showed that the dry air surrounding the “pouch” moved approximately in the same background flow as the moist air within. Despite surrounding it on three sides, little if any of this air appeared to enter the “pouch” (consistent with the increase in TPW). iv) Whereas the strong environmental vertical wind shear may have temporarily decreased the resilience of the “pouch” and temporarily stalled genesis, the critical layer evidently remained resilient enough to keep the proto-vortex intact until it was able to enter a more favorable environment.

The tracking of the parent easterly wave disturbance for 10 days and the maintenance of its structure as it propagated through a hostile environment are consistent with the third hypothesis H3 of DMW09. It is conceivable that the easterly wave was enhanced by the presence of diabatically amplified eddies within the “pouch” and that this hybrid wave-vortex system maintained its coherence and eventually strengthened through this symbiotic interaction.

Following the forecast and diagnostic techniques outlined by WMD09, real time “marsupial forecasts” were produced in support of TCS-08 operations that were able to predict the latitude of tropical cyclone development out to 72 h within 1.5°. These forecasts provided useful insight that raw operational numerical model data could not. As an example, none of the four forecast models used in the experiment predicted a closed low-level cyclonic circulation in the earth-based frame of reference.

While a wealth of data has been presented herein to suggest that the “marsupial way of thinking” can be a useful forecaster/diagnostic tool in the western North Pacific basin during easterly trade wind regimes, much work remains to be done. At the synoptic and sub-synoptic (meso- α) scales, the data does support the tropical cyclogenesis sequence hypothesized by DMW09. The specific mesoscale pathway to the emergent tropical cyclone vortex has yet to be elucidated however. The first hypothesis of DMW09 (H1) states: “*This multi-scale interaction provides a dynamical pathway to “bottom-up” development of the proto-vortex from below*”. The “bottom-

The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



up” pathway to tropical cyclogenesis suggested by Montgomery and colleagues (e.g., Montgomery and Enagonio, 1998; Hendricks et al., 2004; Montgomery et al., 2006) postulates that intense rotating convective cells called vortical hot towers (VHTs) drive the development of the tropical cyclone vortex via low-level convergence and near-surface vorticity spin up that leads the spin up at all levels. The near-surface vorticity anomalies observed in these numerical simulations tend to be collected at low-levels by the diabatically-forced overturning circulation; these vorticity anomalies also undergo a diabatic vortex merger process during active convection or adiabatic merger and vortex axisymmetrization when convection has subsided. Part 2 of this paper will examine aspects of the mesoscale development within the “pouch” of pre-Nuri. Specifically, properties of the convection and kinematic flow observed within the “pouch” will be evaluated using the data from the ELDORA radar in an attempt to assess the contribution of VHTs to development. Aircraft flight level data, SFMR data, and additional remote sensing data (i.e., microwave imagery and Doppler radar) will be used to assess the arguments presented here and further scrutinize the mesoscale evolution for this interesting western North Pacific case.

The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



6 Appendix A: List of acronyms

AXBT	– Airborne Expendable Bathometry Thermograph
CIMMS	– Cooperative Institute for Meteorological Satellite Services, University of Wisconsin
DB	– Depression Beginning
ELDORA	– Electra Doppler Radar
ECMWF	– European Center for Medium-range Weather Prediction Forecasts
ERA-40	– ECMWF Reanalysis Data
GFS FNL	– Global Forecast System Final Analysis
HHC	– Hurricane Heat Content
IR	– Infrared
ITCZ	– Intertropical Convergence Zone
JTWC	– Joint Typhoon Warning Center
MTSAT	– Multi-Functional Transport Satellite
NASA	– National Aeronautics and Space Administration
NOGAPS	– Naval Oceanographic Global Atmospheric Prediction System
NRL	– Naval Research Laboratory
OW	– Okubo-Weiss Parameter
SFMR	– Stepped Frequency Microwave Radiometer
TD	– Tropical Depression
TCS-08	– Tropical Cyclone Structure 2008
TPW	– Total Precipitable Water
TS	– Tropical Storm
USAF	– United States Air Force
VHT	– Vortical Hot Tower

Acknowledgements. Thanks to CIMMS and NASA for satellite data and NRL Stennis for ocean data. This research was supported by the National Science Foundation Grants ATM-0733380, ATM-0715426, ATM-0649944, ATM-0649946, ATM-0227632, and the Office of Naval Research grant N001408WR20129 and by the US Naval Postgraduate School in Monterey, California.

The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



This work was initiated between daily planning meetings and research flights while in the field on Guam, and was soon after completed at the Naval Postgraduate School (NPS). We would like to thank R. Ferek, the ONR/NSF-supported scientists (especially Pat Harr, Russ Elsberry of the NPS and Peter Black of NRL/Monterey), the professional and student forecasters, the flight crews and support personnel who worked tirelessly to make the field campaign a great success. The science team fostered a stimulating atmosphere for conducting tropical cyclone research.

References

- Carr III, L. E. and Elsberry, R. L.: Monsoonal interactions leading to sudden tropical cyclone track changes, *Mon. Weather Rev.*, 123, 265–290, 1995.
- Chang, C. P., Morris, V. F., and Wallace, J. M.: A statistical study of easterly waves in the western Pacific: July–December 1964. *J. Atmos. Sci.*, 27, 195–201, 1970.
- Chen, T. C., Wang, S. Y., Yen, M. C., and Clark, A. J.: Are tropical cyclones less effectively formed by easterly waves in the western North Pacific than in the North Atlantic? *Mon. Weather Rev.*, 136, 4527–4540, 2008.
- Deleon, R. P.: The role of subtropical intrusion in the development of Typhoon Usagi (5W) 2007, MS Thesis, Naval Postgraduate School, Monterey, CA, 118 pp, 2008.
- Dickinson, M. and Molinari, J.: Mixed Rossby–gravity waves and western Pacific tropical cyclogenesis, Part I: Synoptic evolution, *J. Atmos. Sci.*, 59, 2183–2196, 2002.
- Dunkerton, T. J., Montgomery, M. T., and Wang, Z.: Tropical cyclogenesis in a tropical wave critical layer: easterly waves, *Atmos. Chem. Phys.*, 9, 5587–5646, 2009, <http://www.atmos-chem-phys.net/9/5587/2009/>.
- Elsberry, R. L. and Harr, P. A.: Tropical Cyclone Structure (TCS08) field experiment science Basis, observational platforms, and strategy, *Asia-Pac. J. Atmos. Sci.*, 44, 209–231, 2008.
- Ferreira, R. N. and Schubert, W. H.: Barotropic aspects of ITCZ breakdown, *J. Atmos. Sci.*, 54, 261–285, 1997.
- Frank, N. L.: Atlantic tropical systems of 1969, *Mon. Weather Rev.*, 98, 307–314, 1970.
- Glickman, T. S.: Glossary of meteorology, American Meteorological Society Boston, USA, 850 pp, 2000.

The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



- Gray, W. M.: Global view of the origin of tropical disturbances and storms, *Mon. Weather Rev.*, 96, 669–700, 1968.
- Gray, W. M.: Tropical cyclone genesis, Department of Atmos. Sci. Paper No. 323, Colorado State University, Fort Collins, CO, 121 pp, 1975.
- 5 Harr, P. A., Elsberry, R. L., and Chan, J. C. L.: Transformation of a large monsoon depression to a tropical storm during TCM-93, *Mon. Weather Rev.*, 124, 2625–2643, 1996.
- Hendricks, E. A., Montgomery, M. T., and Davis, C. A.: The role of “vortical” hot towers in the formation of tropical cyclone Diana (1984), *J. Atmos. Sci.*, 61, 1209–1232, 2004.
- Holland, G.: Scale interaction in the western Pacific monsoon, *Meteorol. Atmos. Phys.*, 56, 57–79, 1995.
- 10 Lander, M. A.: Description of a monsoon gyre and its effects on the tropical cyclones in the western North Pacific during August 1991, *Weather Forecast.*, 9, 640–654, 1994.
- Leipper, D. and Volgenau, D.: Hurricane heat potential of the Gulf of Mexico, *J. Phys. Oceanogr.*, 2, 218–224, 1972.
- 15 Molinari, J.: Paradigms of tropical cyclogenesis, *B. Am. Meteorol. Soc.*, 85, 662–663, 2004.
- Montgomery, M. T. and Enagonio, J.: Tropical cyclogenesis via convectively forced vortex Rossby waves in a three-dimensional quasigeostrophic model, *J. Atmos. Sci.*, 55, 3176–3207, 1998.
- Montgomery, M. T., Nicholls, M. E., Cram, T. A., and Saunders, A. B.: A vortical hot tower route to tropical cyclogenesis, *J. Atmos. Sci.*, 63, 355–386, 2006.
- 20 Montgomery, M. T., Wang, Z., and Dunkerton, T. J.: Intermediate and high resolution numerical simulations of the transition of a tropical wave critical layer to a tropical depression, *Atmos. Chem. Phys. Discuss.*, accepted, 2009.
- Neumann, C. J.: Global overview, global guide to tropical cyclone forecasting, *World Meteorol.*, 1-1.56, 1993.
- 25 Nguyen, V. S., Smith R. K., and Montgomery, M. T.: Tropical cyclone intensification and predictability in three dimensions, *Q. J. Roy. Meteor. Soc.*, 134, 563–582, 2008.
- Raymond, D. J., Lopez-Carrillo, C., and Lopez Cavazos, L.: Case-studies of developing east Pacific easterly waves, *Q. J. Roy. Meteor. Soc.*, 124, 2005–2034, 1998.
- 30 Reed, R. J. and Recker, E. E.: Structure and properties of synoptic-scale wave disturbances in the equatorial western Pacific, *J. Atmos. Sci.*, 28, 1117–1133, (1971).
- Reed, R. J., Norquist, D. C., and Recker, E. E.: The structure and properties of African wave disturbances as observed during Phase III of GATE, *Mon. Weather Rev.*, 105, 317–333,

The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



1977.

Ritchie, E. A. and Holland, G. J.: Large-scale patterns associated with tropical cyclogenesis in the western Pacific, *Mon. Weather Rev.*, 127, 2027–2043, 1999.

Sadler, J. C.: A role of the tropical upper tropospheric trough in early season typhoon development, *Mon. Weather Rev.*, 104, 1266–1278, 1976.

Sadler, J. C.: Mid-season typhoon development and intensity changes and the tropical upper tropospheric trough, *Mon. Weather Rev.*, 106, 1137–1152, 1978.

Wang, C. and Magnusdottir, G.: The ITCZ in the central and eastern Pacific on synoptic time scales, *Mon. Weather Rev.*, 134, 1405–1421, 2006.

Wang, Z., Montgomery, M. T., and Dunkerton, T. J.: A dynamically-based method for forecasting tropical cyclogenesis location in the Atlantic sector using global model products, *Geophys. Res. Lett.*, 36, L03801, 2009a.

Wang, Z., Montgomery, M. T., and Dunkerton, T. J.: Genesis of pre-hurricane Felix (2007) and the role of the wave critical layer, *J. Atmos. Sci.*, under revision, 2009b.

ACPD

9, 19159–19203, 2009

The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The role of the easterly wave critical layer

M. T. Montgomery et al.

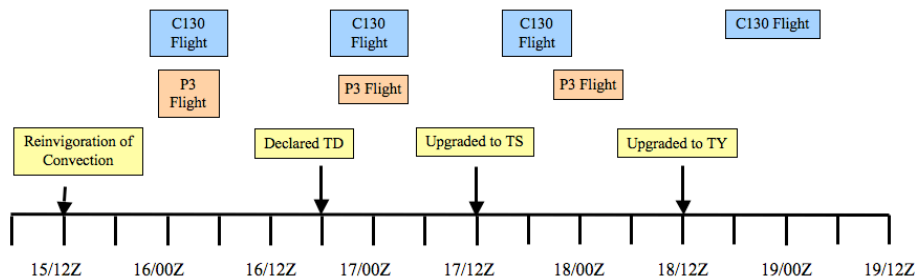


Fig. 1. Timeline of key events during the observational period of Typhoon Nuri during the TCS08 field experiment between 12 Z 15 August and 12 Z 19 August 2008.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The role of the easterly wave critical layer

M. T. Montgomery et al.

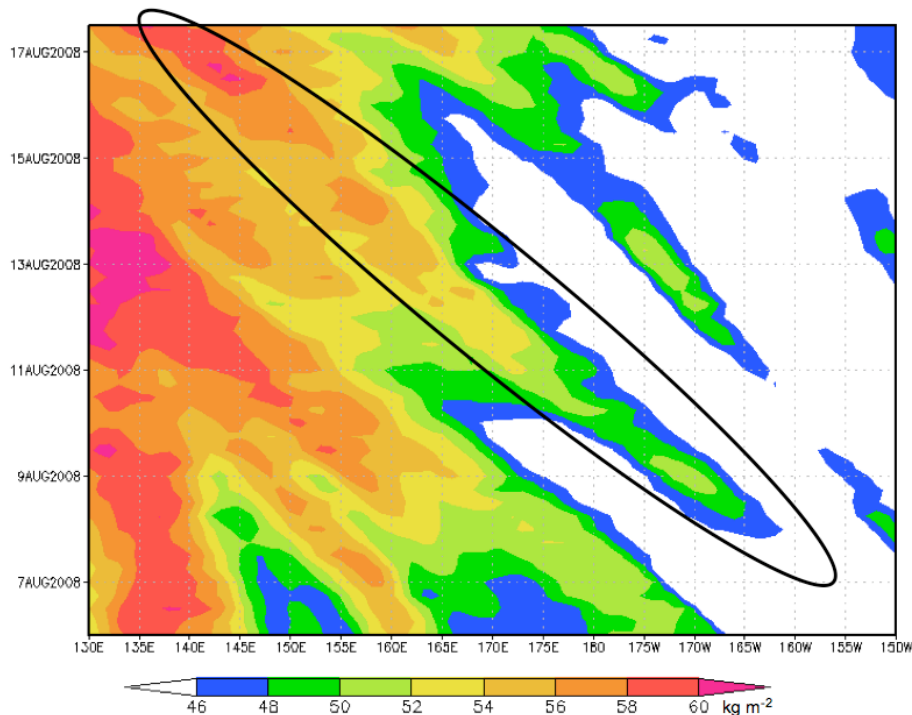


Fig. 2. Latitudinally-averaged (9–17N) GFS FNL TPW Hovmoller valid 00Z 6 August–12Z 17 August (the time when the precursor Nuri disturbance is upgraded to a TS). The black oval highlights the higher moisture content observed in the “pouch” of the pre-Nuri disturbance versus its surrounding environment.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

The role of the easterly wave critical layer

M. T. Montgomery et al.

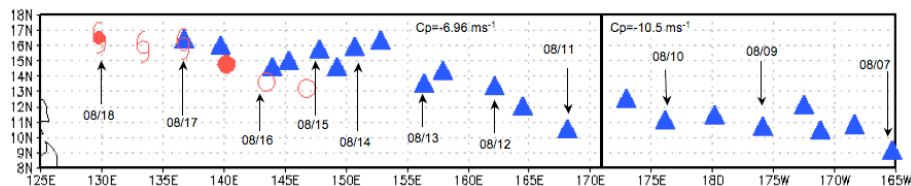


Fig. 3. GFS FNL location of the “sweet spot” (blue triangles) valid at 12 h intervals from 12 Z 7 August–12 Z 17 August. The thick line delineates the time of the change in phase speeds used to calculate the “sweet spot” location. JTWC Best track positions are indicated (red) at 12 h intervals beginning at 00 Z 16 August. An open circle designates an invest and a closed circle a TD. TS and typhoon symbols are shown when storm upgrades occurred. All reference dates represent 12 Z positions.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The role of the easterly wave critical layer

M. T. Montgomery et al.

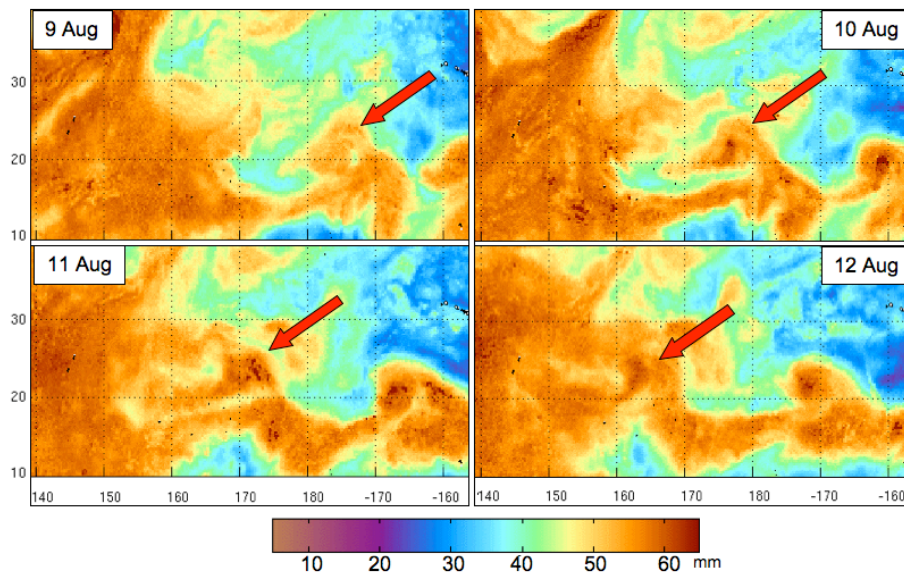


Fig. 4. Four-day time series of CIMMS Morphed TPW valid at 12Z each day. Red arrows point to the location of the “pouch”, which was hypothesized by DMW09 to be an area of increased moisture in the low to mid-troposphere and which helps protect the proto-vortex from lateral intrusions of dry air.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

The role of the easterly wave critical layer

M. T. Montgomery et al.

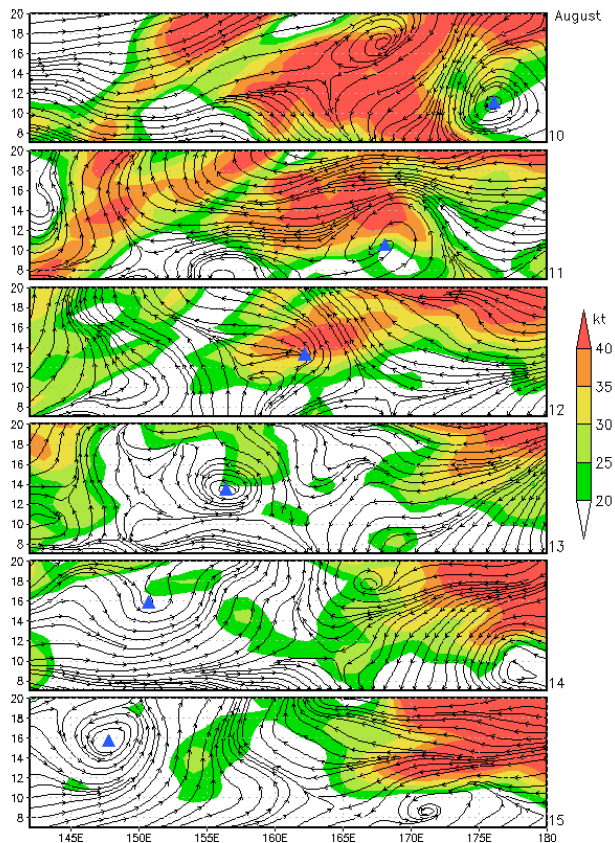


Fig. 5. GFS FNL 850–200 hPa shear (kt, shaded), 925 hPa streamlines in the co-moving frame, and “sweet spot” location (solid blue triangles) valid at 12 Z each day.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The role of the easterly wave critical layer

M. T. Montgomery et al.

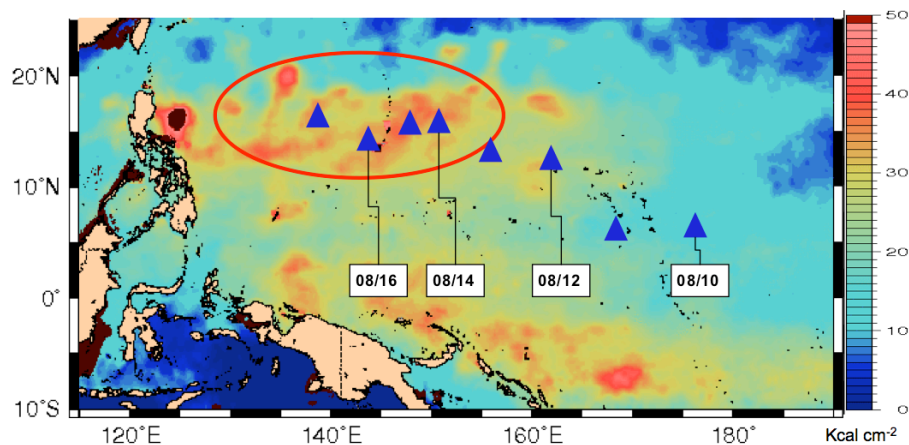


Fig. 6. NRL Stennis HHC analysis valid 12Z 15 August overlaid with the track of the “sweet spot” from the GFS FNL analyses (solid blue triangles). The red oval indicates the area of high HHC that the “pouch” passed over from the time convection was reinvigorated (12Z 15 August) until a tropical storm was declared.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The role of the easterly wave critical layer

M. T. Montgomery et al.

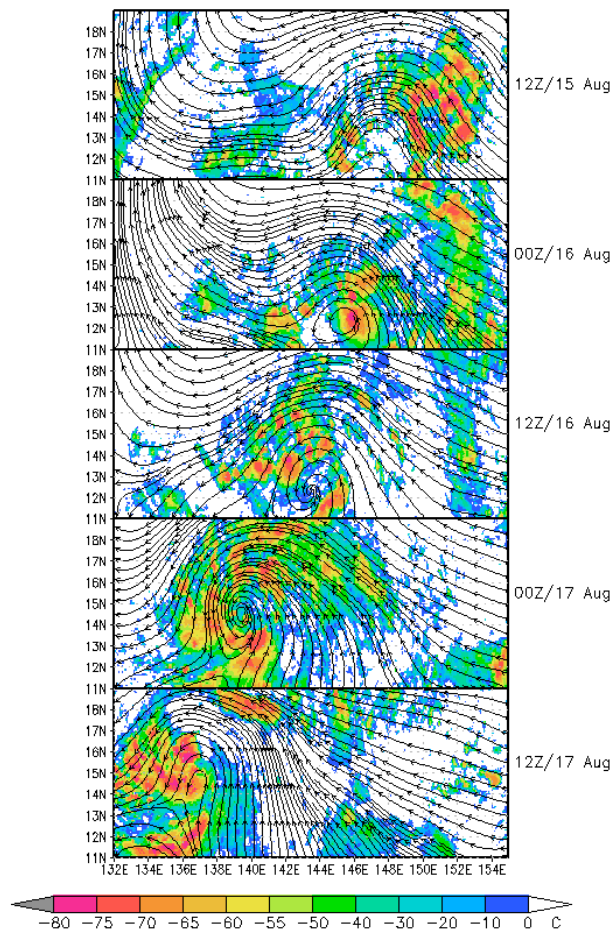


Fig. 7. Time series of GFS FNL 925 hPa streamlines in the resting frame overlaid with MTSAT IR brightness temperature valid every 12 h from 12 Z 15 August to 12 Z 17 August.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The role of the easterly wave critical layer

M. T. Montgomery et al.

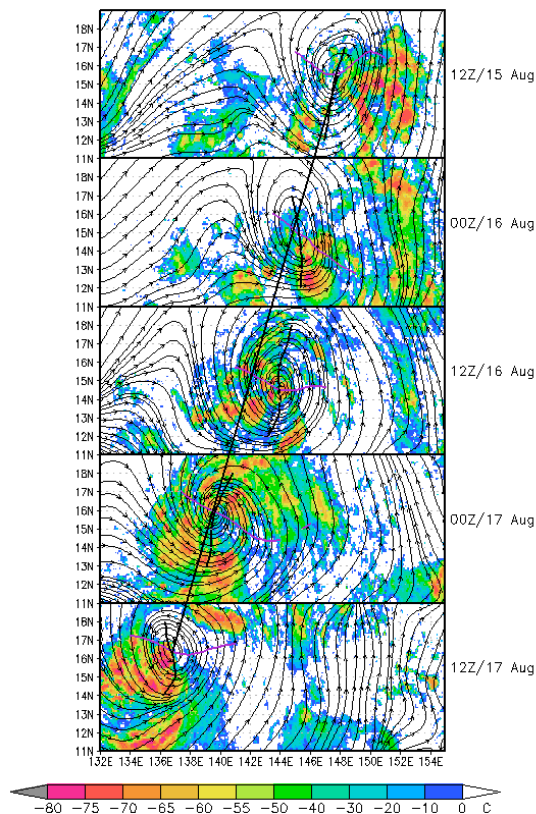


Fig. 8. Time series of GFS FNL 925 hPa streamlines in the co-moving frame overlaid with MTSAT IR brightness temperature valid every 12 h from 12 Z 15 August to 12 Z 17 August. The black line represents the wave trough axis and the purple line the critical latitude as seen by the wave plus sub-synoptic scale flow. The thick black line indicates the propagation of the “sweet spot”.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

The role of the easterly wave critical layer

M. T. Montgomery et al.

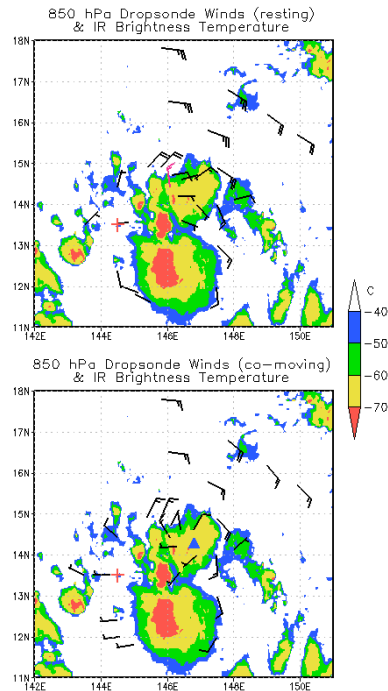


Fig. 9. Combined USAF C130 and NRL P3 850 hPa dropwindsonde observations from the first genesis flight centered on 00 Z 16 August overlaid with MTSAT IR data. Wind barbs are in the resting (top) and co-moving (bottom) frames. Wind speeds are in knots with a full barb representing 10 kt. Magenta barbs indicate winds with a westerly component in the earth-relative frame. The red cross represents the location of Guam (the origin of the flights) and the blue triangle represents the approximate 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 most of the “pouch”.

[Title Page](#)[Abstract](#)[Introduction](#)[Conclusions](#)[References](#)[Tables](#)[Figures](#)[◀](#)[▶](#)[◀](#)[▶](#)[Back](#)[Close](#)[Full Screen / Esc](#)[Printer-friendly Version](#)[Interactive Discussion](#)

The role of the easterly wave critical layer

M. T. Montgomery et al.

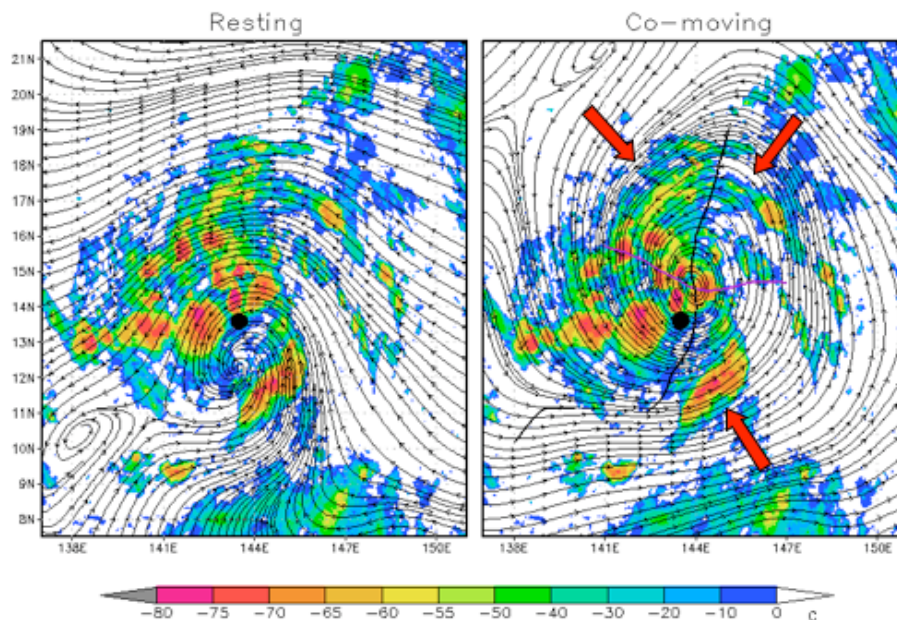


Fig. 10. GFS FNL 925 hPa streamlines in the resting (left) and co-moving (right) frames overlaid with MTSAT IR brightness temperature valid 12 Z 16 August. In the co-moving frame, the black line represents the wave trough axis and the purple line the critical latitude. The red arrows indicate the convective bands spiraling cyclonically inward towards the “sweet spot” in the co-moving frame. The black dot represents the JTWC Best Track position.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The role of the easterly wave critical layer

M. T. Montgomery et al.

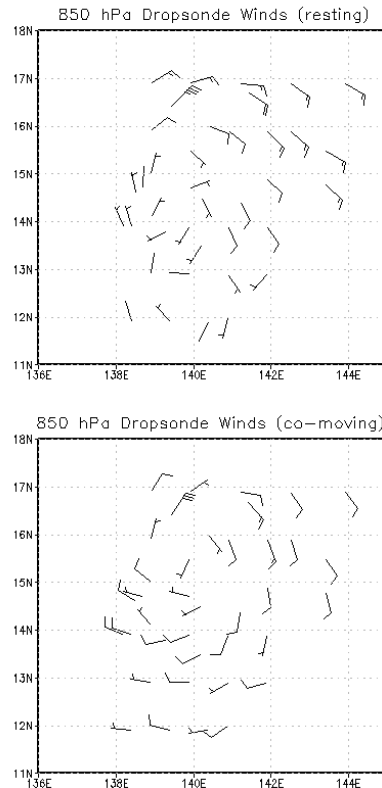


Fig. 11. Combined USAF C130 and NRL P3 850 hPa dropwindsonde observations from the second genesis flight centered on 00Z 17 August in the resting (top) and co-moving frames (bottom). Wind speeds are in knots with a full barb representing 10 kt. The USAF C130 performed a square spiral around the forecasted location of the “sweet spot” and the P3 operated inside of this area.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The role of the easterly wave critical layer

M. T. Montgomery et al.

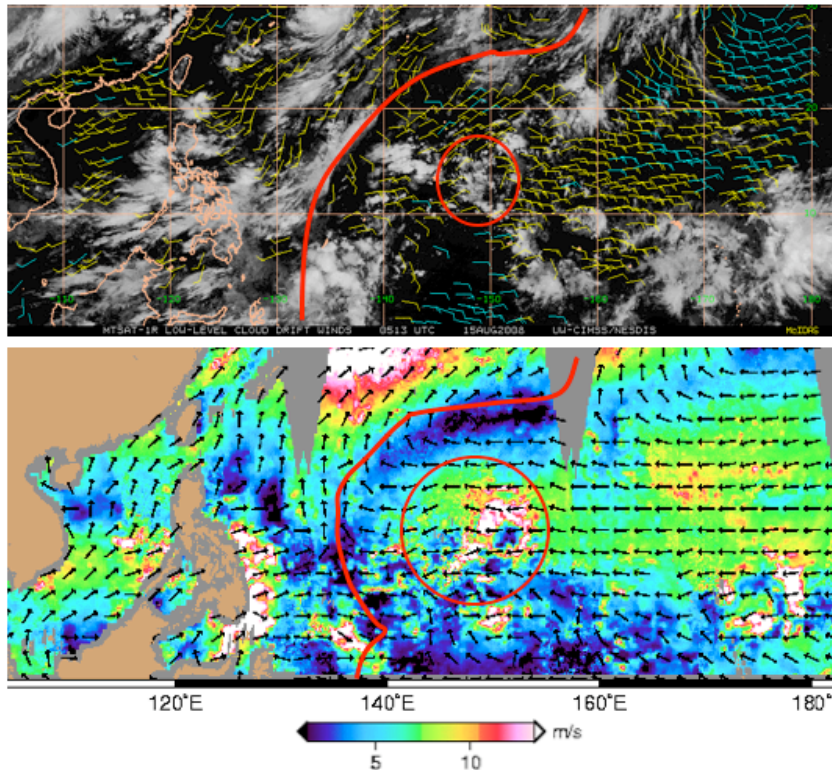


Fig. 12. CIMMS low-level cloud drift winds (top) valid 06 Z 15 August and QuickSCAT Level-3 retrieved wind vectors and wind speed (shaded) valid 15 August (bottom). The blue wind barbs in the CIMMS product are retrievals between the levels of 950–851 hPa and the yellow are retrievals between 850–700 hPa. The red circle highlights the easterly wave that is the precursor to Typhoon Nuri and the red line indicates the easternmost extent of large-scale organized westerly flow. Note that westerly winds are more than 10 degrees from the pre-Nuri disturbance in both analyses.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The role of the easterly wave critical layer

M. T. Montgomery et al.

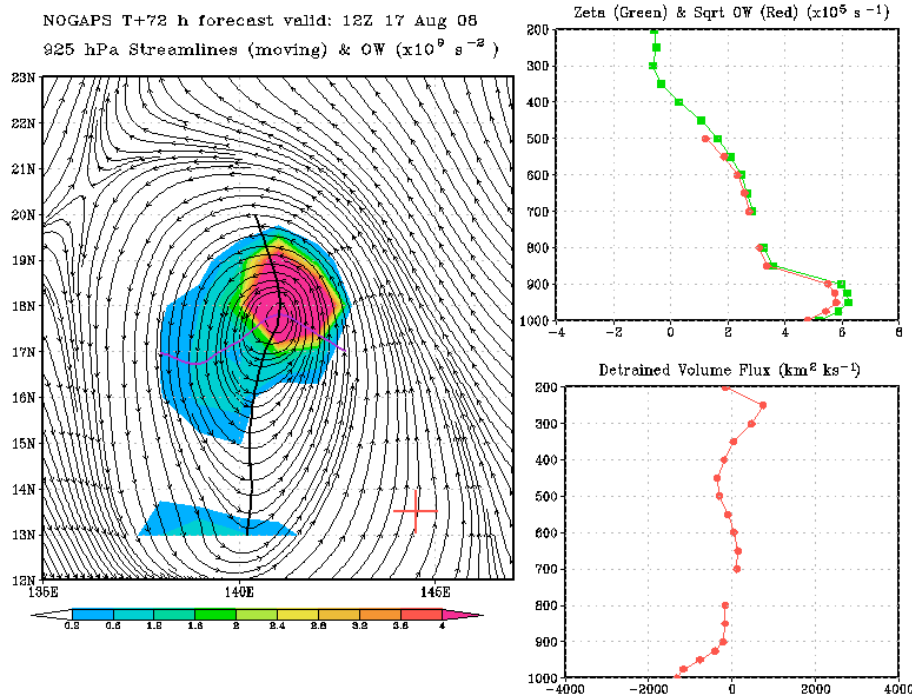


Fig. 13. Real-time 72 h NOGAPS forecast for the potential genesis of Typhoon Nuri. Model initialization time is 12Z 14 August and is valid at 12Z 17 August (time of TS declaration by JTWC). The left panel is 925 hPa streamlines in the co-moving frame with OW (shaded), the wave trough (black line), critical latitude (purple line), and location of Guam (red plus). The right panels are area-averaged diagnostics calculated within a $3^\circ \times 3^\circ$ box moving with the “pouch” so as to quantify the mesoscale nature of these variables within the “pouch”. The top depicts average relative vorticity (green trace) and the average square root of OW (red trace). The bottom is detained volume flux. Unplotted data in the vertical profile are due to missing model data at that level.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The role of the easterly wave critical layer

M. T. Montgomery et al.

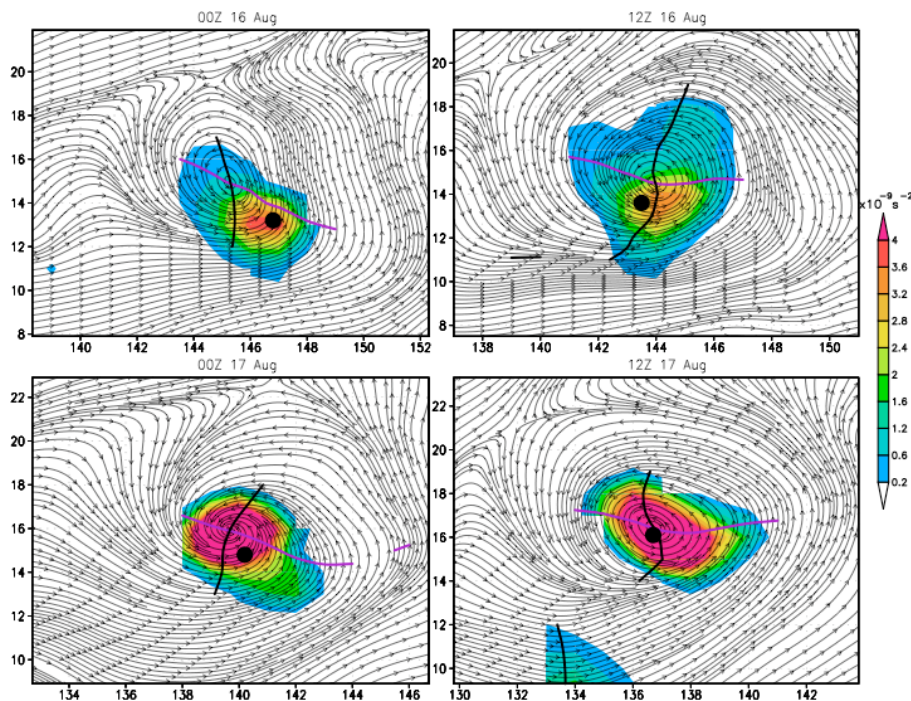


Fig. 14. Thirty-six hour (00Z 16 August–12Z 17 August) GFS FNL time series encapsulating the genesis phase of Typhoon Nuri. Thin black line are 925 hPa streamlines in the co-moving frame, OW is shaded, the thick black line is the wave trough axis, and the purple line the critical latitude. The black dot indicates the JTWC Best Track position. The OW increases in intensity and centers on the “sweet spot” as genesis nears.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



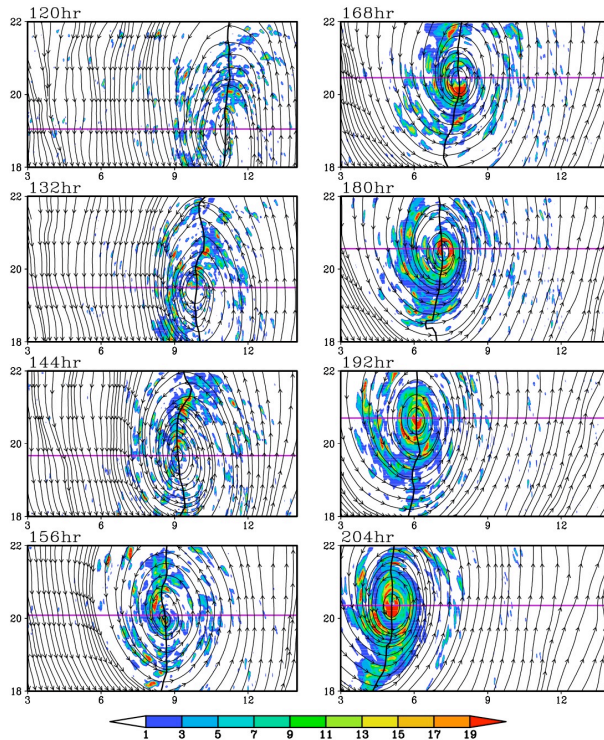


Fig. 15. Summary of idealized numerical simulation of the spatial and temporal evolution of precipitation within the critical layer of a developing easterly wave (Montgomery et al., 2009). The time series depicts surface rain rate (mm h^{-1}), 850 hPa streamlines in the co-moving frame, the wave trough (thick black line), and critical latitude (purple line) at 12 h intervals beginning 120 h into the model run. The abscissa is longitude and the ordinate is latitude. The simulated evolution of precipitation is consistent with the observed data in the pre-Nuri case.

The role of the easterly wave critical layer

M. T. Montgomery et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

