3D.1 ASSOCIATIONS BETWEEN WEST PACIFIC TROPICAL CYCLONES AND HURRICANE SANDY (2012)

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1. INTRODUCTION

Past research has demonstrated associations between western North Pacific recurving tropical cyclones (TCs) and the amplification of the Northern Hemisphere extratropical circulation. In turn, many of these tropical cyclones develop from seedling disturbances that might have evolved in response to forcing from the extratropics. Atmospheric equatorial waves can influence TC genesis in the world's tropical ocean basins by favorably modulating local environmental conditions (e.g., by enhancing low-level convergence and cyclonic relative vorticity) in regions that frequently support TC genesis (e.g., Dickinson and Molinari 2002; Frank and Roundy 2006; Molinari et al. 2007; Schreck et al. 2011; 2012; and others).

Schreck et al. (2012) found that TC genesis over the western North Pacific Ocean is most attributable to tropical-depression-type (TD) and equatorial Rossby (ER) wave disturbances. In reality, many individual western North Pacific TC genesis cases can be attributed to more than one wave type (Schreck et al. 2011). Equatorial waves that contribute to TC genesis are often superimposed on favorable background states associated with larger-scale wavelike phenomena like the Madden-Julian oscillation (MJO; Frank and Roundy 2006). TCs that form in association with equatorial waves often do so in regions where the MJO positively reinforces environmental conditions that favor TC genesis (e.g., Frank and Roundy 2006; Schreck et al. 2011; 2012).

Once TCs form, they often move poleward and interact with the extratropical circulation. Archambault et al. (2013) developed a climatology of TC-extratropical circulation interaction over the western North Pacific Ocean. Their objective was to assess the extent to which recurving TCs modulate the Northern Hemisphere extratropical circulation by exciting Rossby wave trains. Their work analyzed the association between both the size and intensity of cyclones before and after extratropical transition (ET) and the strength of the tropical-extratropical circulation interaction measured by negative potential vorticity (PV) advection by the upper-level divergent outflow associated with the TC, and with convection along the front to the northwest of the TC. They concluded that the most important contributing factor to the modulation of the extratropical circulation following TC recurvature over the western North Pacific Ocean was the strength of the tropical-extratropical circulation interaction, and that stronger interactions tended to occur in late boreal summer and early boreal fall when a precursor upper-level trough was present over East Asia.

This paper primarily examines the development of Typhoon Prapiroon and Tropical Storm Maria in the western North Pacific in early October 2012, and suggests possible links between the simultaneous recurvature of Prapiroon and Maria, the excitation of an extratropical Rossby wave train, and the track of Hurricane Sandy. Section 2 addresses the data and methods employed in this study. Section 3 discusses preliminary results, and section 4 offers preliminary conclusions and ideas for future work.

2. DATA AND METHODOLOGY

NOAA Interpolated outgoing longwave radiation (OLR; Liebmann and Smith 1996) and Climate Forecast System Reanalysis (CFSR; Saha et al. 2010) 850- and 300-hPa geopotential height and wind data were obtained from the Earth System Research Laboratory (ESRL) and the National Centers for Atmospheric Research (NCAR) Computational and Information Systems Laboratory (CISL), respectively. Anomalies were generated by subtracting the first four harmonics of the seasonal cycle and long term mean from each data field.

OLR anomalies were filtered for ER waves by applying a broad rectangular wavenumber-frequency filter after merdionally averaging the data. The chosen filter encompasses OLR anomalies that are characterized by periods of 10 to 100 days and zonal wavenumbers 1-15 westward. Although the broadness of the ER wave filter band might include some signals that are associated with other equatorial wave modes and weather noise, ER waves are known to exhibit different spatial and propagation characteristics in environments characterized by different patterns of vertical wind shear and convection (e.g., Xie and Wang 1996), so the filter band was purposely broadened to identify a more complete spectrum of ER wave OLR signals.

Time-longitude sections of OLR anomalies, and 850- and 300-hPa total and anomalous zonal wind, were generated to identify prominent tropical convective and circulation signals that might have contributed to the development of Prapiroon and

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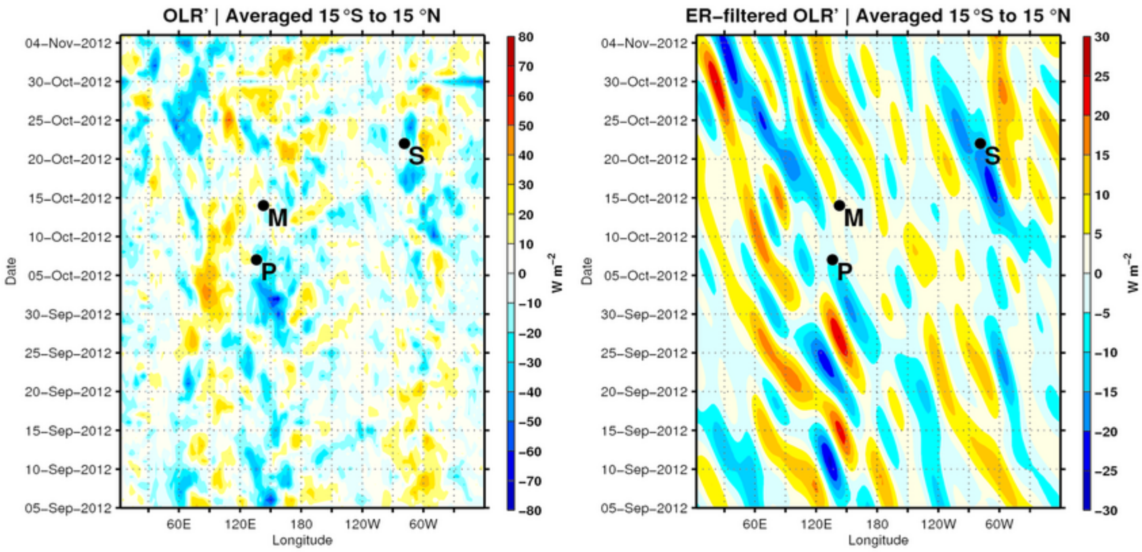

Fig. 1. Time-longitude sections of (a) OLR and (b) ER band filtered OLR anomalies (shaded according to scale in W m^{-2}; see text for filter band description) averaged between 15°S and 15°N. The black filled circles and corresponding letters P, M, and S mark the time-longitude coordinates of genesis dates of Typhoon Prapiroon, Tropical Storm Maria, and Hurricane Sandy, respectively.

Maria. Plan view maps of 300-hPa geopotential height and wind anomalies were also generated for each day of October 2012 to view a continuous evolution of the Northern Hemisphere extratropical circulation response to the simultaneous recurvature of Prapiroon and Maria.

3. RESULTS AND DISCUSSION

3.1 *Origins of Typhoon Prapiroon and Tropical Storm Maria*

Figure 1 shows unfiltered and ER band-filtered OLR anomalies averaged between 15°S and 15°N. These and each of the subsequent time-longitude plots extend from 5 September to 5 November 2012. Prior to 15 October 2012, a quasi-stationary region of negative OLR anomalies (blue shades imply enhanced convection; fig. 1a) is present near 150°E. Prapiroon and Maria (marked by the black circles and corresponding letters “P” and “M”, respectively) attain tropical storm status on the poleward side of this region of enhanced convection on 7 October and 14 October 2012, respectively.

Figure 1b highlights westward-propagating OLR anomalies (some of which are visible in the unfiltered anomaly field) that project onto the ER wave band. Prapiroon appears to form in association with a westward-propagating convective anomaly that dissipates near 135°E on 7 October 2012. The convective anomaly that appears to influence the development of Prapiroon is part of an ER wave “packet” characterized by regions of alternating enhanced and suppressed convection. ER wave packets have been shown to influence TC genesis over the western North Pacific Ocean by establishing concentrated regions of low-level convergence or confluence, low-level cyclonic relative vorticity, and enhanced convection (e.g., Molinari et al. 2007). It is hypothesized that this ER wave packet might have been initiated by equatorward propagating extratropical Rossby waves near the International Date Line (IDL). The links between these two features are discussed further in subsequent paragraphs.

Figure 2 shows time-longitude sections of 300-hPa total and anomalous zonal wind averaged between 10°N and 20°N. This latitude band was chosen for meridional averaging because it includes circulation signals that originate in both the tropics and the extratropics, and thus might better capture relationships between the tropical and extratropical atmosphere. The most prominent large-scale feature in Fig. 2 is a region of zonally narrow 300-hPa westerly winds that is present near the IDL through the entire period of interest (panel a). Upper-level westerlies are anomalous primarily before 10 October (panel b). Regions of upper-level westerly winds extending into the tropics, often referred to as “westerly ducts” (e.g., Tomas and Webster 1994), allow extratropical waves to propagate equatorward and penetrate well into the tropical atmosphere. Although these westerly ducts are most often observed during boreal winter over the eastern Pacific Ocean, they exist at other times of the year, including late boreal summer and boreal fall (e.g., Postel and Hitchman 1999; 2001), and can occur at any time of the year when generated by favorable combinations of interannual and intraseasonal signals.

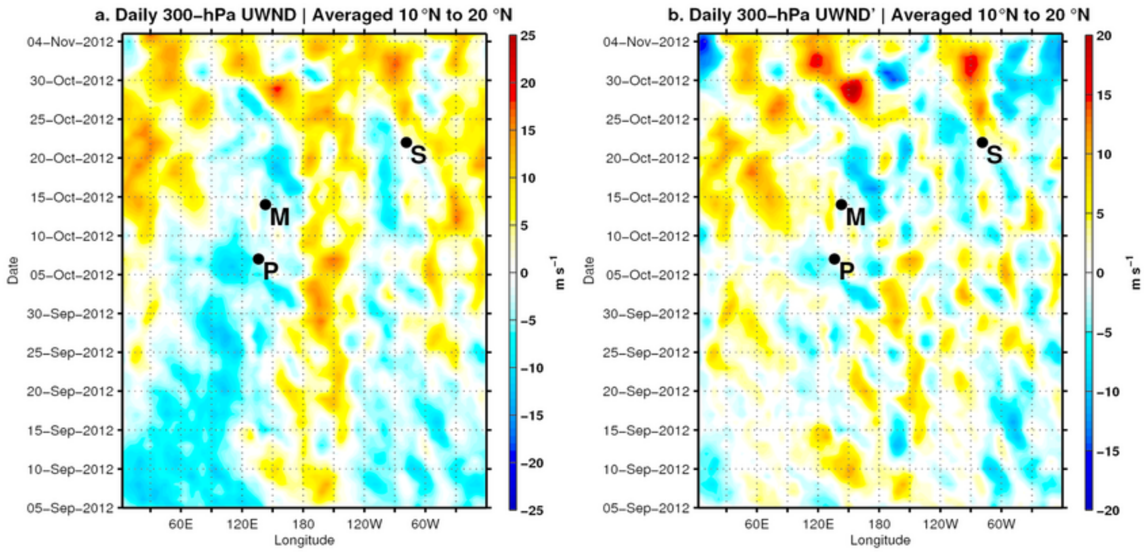

Fig. 2. Time-longitude sections of (a) 300-hPa zonal wind and (b) anomalous 300-hPa zonal wind (shaded according to scale in m s^{-1}) averaged between 10°N and 20°N. The black filled circles and corresponding letters follow the description of Fig. 1.

Meehl et al. (1996), Slingo (1998), and Kiladis (1998) demonstrated associations between equatorward propagating upper-level extratropical Rossby waves over the East Pacific during boreal winter, and the excitation of convective and circulation anomalies that resemble ER waves. Each study suggested that upper-level troughs accompanying equatorward wave propagation from the extratropical North Pacific modulate convection in and around the Intertropical Convergence Zone and excite ER wave circulation and convective responses. The ER wave packet in Fig. 1 is located on the western fringe of anomalous upper-level westerlies near the IDL in early September, suggesting that repeated upper-level trough intrusions might have contributed to the organization of the ER wave packet over the western Pacific Ocean.

Figure 3 follows the time-longitude sections displayed in figure 2, except 300-hPa zonal wind anomalies are replaced by 850-hPa zonal wind. Prapiroon and Maria form near a region of enhanced low-level convergence, where low-level westerlies meet trade easterlies. Frank and Roundy (2006) used composites of 850-hPa wind and OLR anomalies related to different types of equatorial waves to demonstrate the effects of equatorial waves on TC genesis. The ER wave composite (their Fig. 7b) suggested that TCs most often form in regions of enhanced low-level confluence or convergence associated with the ER wave circulation. The 850-hPa wind pattern in Fig. 3b is consistent with their work.

Figure 4 shows time-averaged 300-hPa geopotential height anomalies and 850-hPa total wind in plan view form. Data are averaged over a period extending from 1 October to 15 October 2012, which spans the genesis times of Prapiroon and Maria. An anomalous 300-hPa ridge exists poleward of 15°N, between 150°E and the IDL. Equatorward of the anomalous ridge is a low-amplitude trough anomaly that appears to be connected to a higher-amplitude trough anomaly at the upper right of the plot. The configuration of the anomalous ridge-trough pattern over the tropical and subtropical North Pacific resembles an anticyclonic wave-breaking pattern, which helps to deposit extratropical upper-level troughs deep into the tropics. The trough anomaly equatorward of 15°N is associated with upper-level westerly winds on its equatorward side (not shown). The presence of the upper-level trough anomaly demonstrates the link between equatorward propagating extratropical Rossby waves and the region of enhanced upper-level westerlies near the IDL.

Prapiroon and Maria appear to have formed on the eastern and equatorward side of a broad low-level cyclonic gyre located north of the equator between 120°E and 150°E. A less defined clockwise circulation straddles the equator to the south of the main cyclonic gyre. This low-level circulation structure resembles the one shown in Molinari et al. (2007; their Fig. 6) that accompanied what was identified as an ER wave packet over the western Pacific Ocean during late boreal summer and fall of 1991. Several tropical cyclones formed in association with the Northern Hemisphere gyre accompanying that ER wave packet.

Figure 4 suggests that Prapiroon and Maria formed in a region of low-level convergence or confluence accompanying the ER wave circulation over the western North Pacific Ocean. Anomalous convection was present on the eastern and equatorward side of the gyre when both Prapiroon

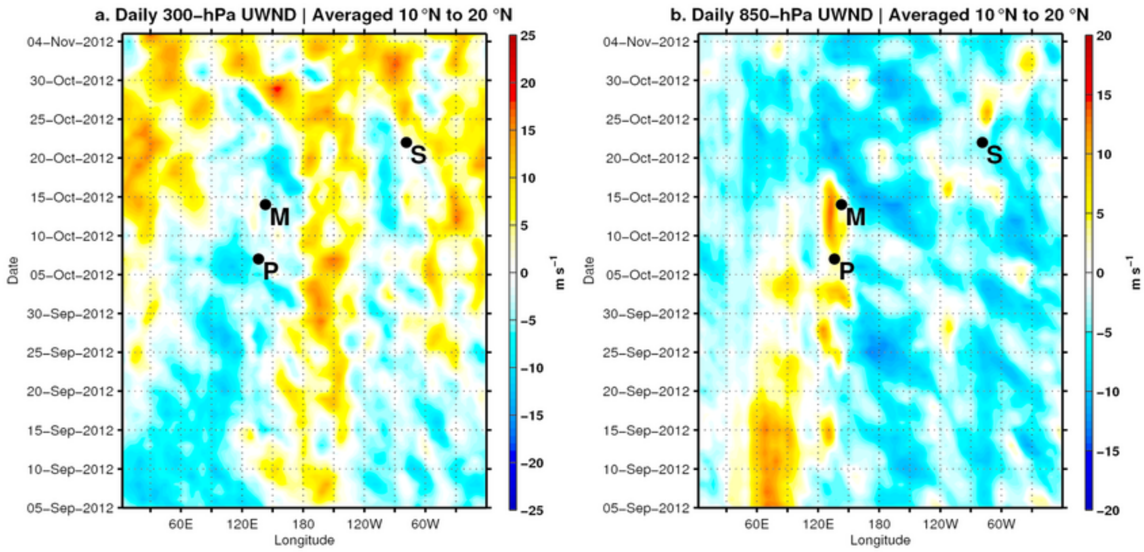

Fig. 3. (a) As in Fig. 2a. (b) Time-longitude section of 850-hPa zonal wind (shaded according to scale in m s^{-1}) averaged between 10°N and 20°N. The black filled circles and corresponding letters follow the description of Fig. 1.

and Maria attained tropical storm strength (not shown), but the extent to which the ER wave and TCs contributed to this convective signal remains in question.

3.2 *Tropical-extratropical Circulation Interactions Following Recurvature*

This subsection briefly addresses links between the simultaneous recurvature of Prapiroon and Maria, the excitation of a Rossby wave train across the North Pacific and North America, and the track of Hurricane Sandy as it moved poleward along the coastline of Eastern North America. Analyses presented here are incomplete and therefore warrant further investigation.

Figure 5 shows the evolution of the Northern Hemisphere 300-hPa geopotential height and wind anomaly pattern in three-day increments, beginning on 18 October 2012 (panel a). Prapiroon and Maria, whose positions are shown by the red “x” markers and corresponding letters, are still recurving over the western North Pacific on 18 October 2012. Anticyclonically curved wind anomalies poleward

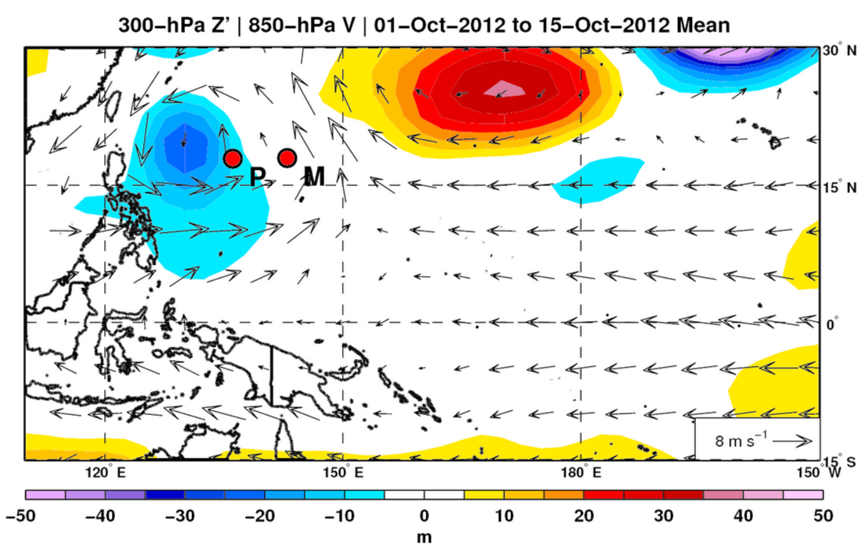

Fig. 4. 300-hPa geopotential height anomalies (shaded according to scale in m) and 850-hPa total wind. Data is averaged over a period extending from 1 October to 15 October 2012. The red circles and corresponding letters “P” and “M” mark the locations of Prapiroon and Maria, respectively, when they first attained tropical storm status.

of Prapiroon and Maria suggests the presence of an enhanced subtropical jet on the poleward side of a developing upper-level ridge anomaly to the east of Japan. On this day, Prapiroon was located near the equatorward entrance region of an amplifying jet streak (not shown). An anomalous upper-level trough is located to the west of the developing upper-level ridge, which has been identified as a precursor signal to TC-extratropical circulation interaction events by Archambault et al. (2013).

Prapiroon and Maria have already undergone ET by 21 October 2012 (Fig. 5b). In the wake of their simultaneous recurvature, the ridge anomaly first identified in panel (a) has amplified and extended poleward of 75°N over Alaska. In response to the amplifying ridge, a trough anomaly that was present over the Gulf of Alaska in panel (a) has deepened and moved equatorward and eastward. This trough anomaly will later interact with Sandy over Eastern North America and the western North Atlantic.

By 24 October 2012 (Fig. 5c), the North Pacific ridge anomaly has amplified considerably in response to the eastward movement of the trough anomaly that was present over Northeast Asia in panels (a) and (b). The deepening trough anomaly located over the U.S. Pacific Northwest region has remained nearly stationary over the three-day increment, but an equatorward-extended portion of the upper-level ridge over the Bering Strait, suggested by the total 300-hPa geopotential height field (black contours near 150°W), will soon help to reinforce the eastward movement of the upper-level trough anomaly over Western North America. Farther downstream, a weak upper-level trough anomaly is visible over the eastern Gulf of Mexico. This trough anomaly is already beginning to interact with Sandy.

The final panel in Fig. 5, corresponding to 27 October 2012, shows the eastward movement of the trough anomaly that was three days earlier centered over the Pacific Northwest. The trough anomaly has expanded equatorward and linked with the eastern Gulf of Mexico trough anomaly. The eastern side of the larger trough anomaly interacts with Sandy east of the state of Florida. This anomalous trough prevents Sandy from moving away from the coastline of Eastern North America in subsequent days.

4. CONCLUSIONS AND FUTURE WORK

The origins of two recurving western North Pacific tropical cyclones—Typhoon Prapiroon and Tropical Storm Maria—were discussed. Links between these recurving tropical cyclones, the excitation of a Rossby wave train over the North Pacific and North America, and the track of Hurricane Sandy were then suggested.

Prapiroon and Maria developed over the western North Pacific Ocean in October 2012 in association with an ER wave packet that is hypothesized to have been triggered by equatorward propagating extratropical Rossby waves in the vicinity of the International Date Line. Prapiroon and Maria formed in a region of low-level convergent flow and enhanced convection on the eastern and equatorward side of a broad low-level cyclonic circulation associated with the ER wave

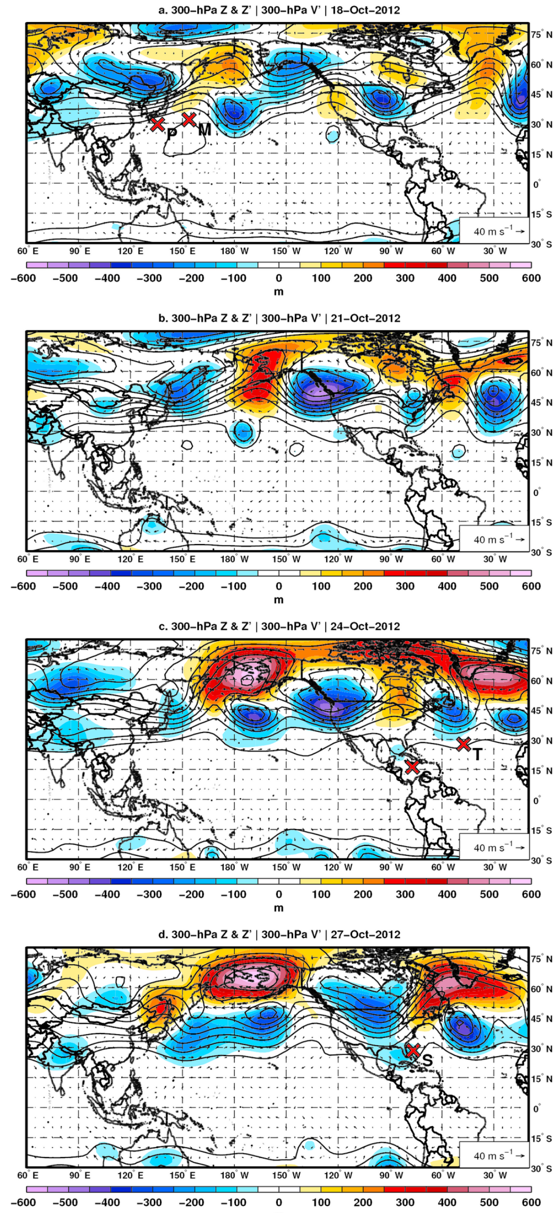

Fig. 5. 300-hPa geopotential height (shaded according to scale in m) and wind anomalies (m s^{-1}; a reference vector located at the bottom right of each panel). Panels are plotted in three-day increments. The red "x" markers and corresponding letters "P" and "M" and "S" mark the locations of Prapiroon, Maria, and Sandy on the days corresponding to each plot. Storms are only labeled if they have attained a minimum of tropical storm status.

packet. These two TCs later recurved simultaneously and excited an extratropical Rossby wave train over the North Pacific and North America. A trough anomaly that originated over the Gulf of Alaska moved equatorward and eastward in response to the amplification of the Rossby wave train and later interacted with Hurricane Sandy over the western North Atlantic.

This paper only presents a preliminary analysis of the origins of Prapiroon and Maria and their links to Hurricane Sandy. The origin of the ER wave packet over the North Pacific Ocean, and its contribution to the genesis of Prapiroon and Maria, warrants further investigation. Additionally, an assessment of the strength of the TC-extratropical circulation interaction over the North Pacific accompanying the simultaneous recurvature of Prapiroon and Maria will be a focus of future work. This assessment will follow a technique employed by Archambault et al. (2013) that uses the negative advection of PV by the upper-level divergent outflow associated with TCs as a metric to assess the strength of the interaction between Prapiroon, Maria, and the extratropical circulation. The author believes that this assessment will provide more conclusive results regarding the extent to which Prapiroon and Maria contributed to the excitation of an extratropical Rossby wave train over the North Pacific and North America that later influenced the track of Sandy.

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