An analysis of the formation and evolution of the 1989 Western North Pacific subtropical gyre

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ABSTRACT

This thesis conducts an observational study of a large cyclonic gyre that developed in the Western North Pacific (WNP) in late July 1989. For a period of six days, azimuthally-averaged winds at 850 hPa remained cyclonic out from the center of circulation to the 2000 km radius, with azimuthally-averaged tangential wind speeds at or greater than 10 m s\(^{-1}\). The gyre exhibited an asymmetric convection pattern, with the center, north and west flanks devoid of large convective areas, but the southern and eastern flanks maintained large-scale convective regions, extending as much as 4000 km in longitude.

Prior to gyre formation, an active MJO existed over the Indian subcontinent. The active MJO helped create an anomalously strong upper-tropospheric jet over central Asia and a jet exit region over northeastern Asia and the WNP. This created a favorable equatorward wave-breaking environment that allowed an upper-tropospheric trough to penetrate from the midlatitudes into the subtropics, and deposit a cutoff low in the WNP. Cyclonic vorticity maxima coming from the west engaged the upper-level low, with several orbiting the upper-level cyclone, and establishing a large-scale cyclonic circulation. A second wave-breaking event expanded the size of the subtropical gyre and helped create the eastern flank of convection.

This case is compared in detail to a 1988 case examined by Molinari and Vollaro (2012), which also developed during an active MJO in the Indian Ocean. Gyre-related disturbances and the possibility of Rossby wave dispersion are also examined.
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I. Introduction

1.1 Overview

The Western North Pacific (WNP) plays host to a variety of synoptic-scale meteorological phenomena during the boreal summer, and the origins of these events range from the tropical latitudes through the subtropics and into the extratropical activity of the mid-latitudes. One such phenomenon is a large low-pressure area that encompasses a sizable fraction of the subtropical WNP. While its presence is not unusual, there is no established nomenclature to describe the feature; Harr et al. (1996) and Holland (1995) describe the feature as “a monsoon depression”, while Carr and Elsberry (1995) use the term “monsoon cyclone”, and Lander (1994), Chen et al. (2004) and Molinari et al. (2007) establish the feature as a “monsoon gyre”. Most recently, Molinari and Vollaro (2012) call the feature a “subtropical gyre”, referencing its location in the subtropical latitudes, 1000 km north of the latitude of the long-term monthly mean axis of the monsoon trough (Lander 1994). In all cases, the center is usually devoid of substantial convection, and light winds will extend out from the center for a radius of 100-200 km. Lander (1994, 1996) use the “monsoon gyre” term to distinguish the feature from subtropical lows that are smaller and have more symmetric distributions of convection. In an effort to maintain as accurate a description of the feature as possible, the Molinari and Vollaro (2012) terminology of a “subtropical gyre” is used here.

Subtropical gyres have distinct characteristics that make them unique among WNP disturbances. While the gyre center is often devoid of cloud cover, there is extensive and deep convection on its equatorward and eastward sides (Lander 1994;
Molinari et al. 2007). Tropical cyclones will often develop in the convection east of the center and move in a cyclonic orbit around the gyre center. The description of their duration and rate of occurrence varies widely. Lander (1994) suggests that gyres have a life span approximately two to three weeks, and develop once every other year on average. Chen et al. (2004) conducted a study on the frequency of subtropical gyre occurrences, considering a feature to be a gyre if its lifespan is 5 days or greater and concluded gyres occur several times per year. No formal study of the rate of occurrence of subtropical gyres (as described in the following section) has been undertaken.

1.2 Literature Review

Of the studies that have been conducted on subtropical gyres, the most focus has been applied to a gyre that developed in the WNP in August 1991. Among those that extensively reviewed this case was the first published paper on subtropical gyres, by Lander (1994), who conducted an analysis of the August 1991 subtropical gyre as well as a brief overview of a subtropical gyre that developed in July 1993. Lander (1994) examined sequences of satellite images, and operational numerical analyses of sea level pressure and 500-hPa heights. Lander (1994) describes that in the WNP summer, the monsoon trough, a low-pressure trough with deep southwesterly wind flow to the south of the trough axis, is typically present. On average, the monsoon trough extends eastward from the South Asian low-pressure trough, extending roughly northwest-southeast over the tropical WNP, loosely anchored to the areas of highest sea surface temperatures (Sadler et al. 1987). It is common for the trough to migrate and to change shape and orientation, ranging from 5° N to 25° N, and may adjust to an east-west or southwest-northeast orientation. The monsoon trough serves as a linear shear zone between
monsoon southwesterlies to its south and the easterly winds to its north, with most of the deep convection occurring south of the trough axis. Lander (1994) contrasts the appearance of the low-level circulation that occurs with the subtropical gyre to the physical characteristics of the monsoon trough, and describes six features that characterize the low-level circulation of the subtropical gyre:

(1) A large, low-level cyclonic vortex, with nearly circular isobars, the outermost possessing a 2500 km diameter;

(2) A 1000 km northward displacement of the SLP minimum with respect to the axis of the long-term mean monsoon low-pressure trough;

(3) A north-south oriented, low-level high-pressure ridge that separates the SLP depression associated with the gyre from the low-pressure area over the Asian landmass;

(4) Deep, sustained convection rimming the southern and eastern periphery of the circulation;

(5) Production of a sequence of mesoscale vortices (which may become TCs) that emerge from the downstream end of the peripheral cloud band; and

(6) A two to three week life span.

Although Lander (1994) considers the possibility of intermediate configurations between the subtropical gyre and the monsoon trough, it is stressed that the two are different enough from each other that they can be easily discerned.

In the analysis of the meteorological events that led to the formation of the 1991 subtropical gyre, Lander (1994) proposed that the gyre has links to extratropical activity,
though the extent of the midlatitude forcing is unclear. The entire life cycle of the gyre, including formation, maturation and decay, took place over a period of 27 days, but Lander (1994) does not firmly establish a date where the monsoon circulation clearly acquires gyre characteristics. In discussion of impacts on tropical cyclone (TC) development, Lander (1994) explained that TCs interact with the gyre vortex in a form of binary interaction, where the effects are dependent on the size and depth of the individual vortices (Ritchie and Holland 1993).

Lander (1994) also briefly reviewed the July 1993 gyre in regards to its formation and impacts. In this case, a large-scale cyclonic vortex developed by 0000 UTC 21 July 1993, and over the next ten days, three midget TCs spun up in the eastern convection, in a similar fashion to the first three TCs in the 1991 case. The gyre migrated westward during its lifetime, and was no longer distinguishable after it merged with a low-pressure area over the Asian continent on 1 August. In this case, no giant TC developed, and the gyre center first formed 20° to the west of the 1991 case, but at about the same latitude. Lander (1994) advances the idea that the shorter life span and/or proximity to the Asian landmass may have prohibited the 1993 case from being as intense as the 1991 gyre.

A second paper that extensively analyzed the August 1991 case is Holland (1995). In this paper, it is stated that the active convective region on the eastward side of the mature subtropical gyre occurs in an area of strongly confluent low-level flow between the monsoon westerlies and central Pacific easterlies. In describing the formation of the gyre, Holland (1995) complements the findings of Lander (1994) by providing further detail, indicating that as the 1991 subtropical gyre developed, it doubled its low-level tangential wind velocity over a period of five days, to 20 m s$^{-1}$ by 10 August.
In investigating the formation of the gyre, Holland (1995) proposes that the 1991 subtropical gyre may have formed following the passage of a mid-latitude frontal trough pushing equatorward, when prolonged diabatic heating produced a favorable environment for wave growth by exciting equatorial waves in the region. Relying on the idealized solutions of heat-induced tropical circulation by Gill (1980), it is stated that sustained diabatic heating would produce an Equatorial Rossby wave response that would in turn produce a gyre and equatorial westerlies to the west of the primary area of heating (in a highly-dispersive tropical atmosphere). In the 1991 case, the gyre developed to the west of deep convection, giving credence to the hypothesis of Holland (1995). Further support was garnered by simulating the diabatic heating using a non-linear baroclinic model on a beta-plane valid at 20° N and integrated over 144 hours. The output produces a large-scale cyclonic circulation similar to the structure observed in the circulation of the subtropical gyre, with southwesterlies east-southeast of the area of heating.

Holland (1995) goes on further to provide an overview of the structure of the 1991 subtropical gyre, identifying an anticyclonic “negative gyre” near the surface south-southeast of the main gyre, promoting cross-equatorial flow into the low-level monsoon westerlies, and the formation of a strong, narrow monsoon jet in the southern and eastern quadrants of the gyre. In discussion of the formation of vorticity maxima within the gyre circulation, Holland (1995) proposes that clusters of thunderstorms known as mesoscale convective systems (MCS) develop via a complex process involving diabatic heating, and following Mapes (1993), the growth of an initial MCS encourages the growth of MCS nearby. Surface vortices may develop in the vicinity of the MCSs.
In discussion of how the subtropical gyre interacts with the extratropics, Holland proposes that the most significant interactions occur from the poleward movement of TCs that develop within the eastern quadrant of the subtropical gyre and separate from the main circulation, a process described as highly non-linear and complex.

Taking a different perspective, Molinari et al. (2007) examined the 1991 gyre case in relation to equatorial waves. Initially, the study conducted in this paper was to further understand the formation of the 1991 gyre and its role in tropical cyclogenesis, but the authors evolved their focus as it was realized that the subtropical gyre was part of a longer-lasting Equatorial Rossby (ER) wave packet (a large-scale, low-frequency westward moving atmospheric wave disturbance (Holton 2004)), which appeared to represent the fundamental dynamical component of the flow. Therefore, the focus of this paper was less on the gyre and more on the large-scale, longer-period wave environment that the gyre was a part of. A 15-40 day bandpass filter was applied to the wave packet to emphasize the waves in the analysis of the time series. It was shown that a westward-moving packet of equatorial waves dominated the area between 5°N and 20°N from the beginning of August to the end of October, with the gyre appearing in the first transition period from northerly wind components to southerly wind components. The mean wavelength and period of the wave packet were 3600 km and 22 days, +/-10% over the life of the packet. This gives a phase speed of about -1.9 m/s (1.9 m/s westward). In their analysis of the ER wave packet, the authors state that only the initial low met the definition of a subtropical gyre as stated by Lander (1994).

Molinari et al. (2007) obtain findings similar to Lander (1994) and Holland (1995), using the OLR and 850-hPa vorticity maps of early August 1991 produced by
Lombardo (2004). In agreement with the results of Holland (1995), the gyre was found to have formed just to the west of the area of strongest heating, and Molinari et al. (2007) concur with Lander (1994) and Holland (1995) that the gyre formed in a region of persistent active convection. Since off-equatorial symmetric heating projects efficiently onto ER waves (Zhang and Webster 1992; Hoskins and Yang 2000), Molinari et al. (2007) argue that that the heating associated with the convection during the development period of the monsoon gyre excited the initial ER wave low. The stationary ER wave packet intensified in the convergent background flow associated with the monsoon trough, so the gyre simply appears as the initial low in the ER wave packet.

Molinari et al. (2007) also evaluated the tropical cyclones that developed in close proximity to a composite ER wave low comprised of the subtropical gyre and the other lows of the ER wave packet. It was determined that development was unfavorable in the southern convection of the composite ER wave low due to high vertical wind shear, and while wind shear was weakest northeast of the center of the composite ER wave low, TCs did not form in this region because it was convectively inactive. In the favored region of TC development east and southeast of the center, storms were able to develop in a region of moderate wind shear and strong convection and cyclonic vorticity, but the wind shear generally prevented significant strengthening of the TC while under the influence of the gyre. A study by Frank and Roundy (2006) is consistent with this result for favored regions of TC development, demonstrating tropical cyclogenesis in the WNP occurs a few hundred kilometers southeast of a composite ER wave low. It is notable that while the composite included both the subtropical gyre and subsequent lows, all the developing TCs formed east or southeast of the low pressure center.
In contrasting the lifespan of the August 1991 gyre(s), each paper has its own conclusion. In Lander (1994), there is only one gyre. Holland (1995) proposes that there were two gyres, both of which were lifted into the extratropics after TCs merged with their centers. Molinari et al. (2007) propose that the first gyre was the initial low in a stationary ER wave packet. Between Holland (1995) and Lander (1994), the divergence of opinion stems from a difference in interpretation; Lander (1994) interprets the gyre as having remained in place as the giant TC that merged with its center lifts northward, while Holland (1995) takes the opinion that the first gyre also moved northward with that TC, and then a second gyre forms in roughly the same location as the initial gyre, and when the second gyre moves into the extratropics, the event is complete. Molinari et al. (2007) suggests in their analysis of the ER wave packet that the initial low that was the subtropical gyre began to give way to a ridge of high pressure at the longitude of the subtropical gyre around 28 August, which would be in agreement with the findings of Lander (1994). It is important to note that Molinari et al. (2007) suggests that the gyre was part of a much larger timescale ER wave packet, whereas Lander (1994) makes no such assertion.

In growth mechanisms for the gyre, the three papers are fairly consistent. All three attribute the growth of the subtropical gyre to a localized region of strong heating in early August. However, the way they arrive at this conclusion varies between the three papers. The explanation given by Lander (1994) is based strictly on observed evidence and does not delve into the dynamics or physics associated with the development of the subtropical gyre. Holland (1995) uses idealized models, but his evidence is otherwise circumstantial and are not particularly well-explained by the theories he provides; the
applicability to subtropical gyres in general may be limited. Both Holland (1995) and Molinari et al. (2007) note that there would be an excitation of ER waves, with Holland basing his statement after the idealistic models of Gill (1980), and Molinari et al. (2007) make this statement based on the work of Zhang and Webster (1992) and Roundy and Frank (2006).

In broader perspective, Chen et al. (2004) also conducted a review of subtropical gyres. The definitions that the authors use are generally the same as those from Lander (1994). Chen et al. (2004) also establish their radius at 1250 km, but the life span to meet their interpretation of a gyre is shorter, at ≥5 days rather than the 2-3 weeks suggested by Lander (1994). Chen et al. (2004) used this modified version of the subtropical gyre definition to conduct a search for subtropical gyre occurrences based on JMA tracks from 1979-2002 for tropical storms and typhoons, and JTWC tracks from 1979-2002 for tropical depressions. Chen et al. (2004) recognize subtropical gyres based on precipitation datasets and Outgoing Longwave Radiation (OLR) data. The July 1989 case examined in this thesis is mentioned as an example of a subtropical gyre, but is not discussed in detail. A concern with the work of Chen et al. (2004) is that they might be capturing other synoptic-scale cyclonic features that are not gyres, for instance, an existing large TC in the WNP. Chen et al. (2004) state an average of 57.3 days in a given year have subtropical gyre activity (in contrast to once every two years as suggested by Lander (1994)), a value which lends support to the idea that their subtropical gyre term may be too broad and include non-gyre features.

Most pertinent to the research undertaken with this thesis is a detailed analysis of a July 1988 subtropical gyre conducted by Molinari and Vollaro (2012) (henceforth
MV2012). MV2012 can in many ways be seen as a predecessor to the work conducted with the July 1989 gyre, and as a result this literature review attempts to discuss their work in considerable detail.

The July 1988 gyre developed during an active phase of the Madden-Julian Oscillation (MJO) (Madden and Julian 1972) over the Indian Ocean, which through diabatic heating from enhanced convection, contributed to an anomalous upper tropospheric westerly jet over the northeast Asian coast, and a jet exit region over the northwest Pacific Ocean. Downstream of the jet exit region, multiple equatorward wave breaking events occurred (also known as anticyclonic wave breaking events or “LC1”, Thorncroft et al. 1993), leaving behind a region of low-level cyclonic vorticity and convection that would provide the incipient disturbance for the development of the subtropical gyre. A second wave breaking event was responsible for large-scale subsidence to the north of the gyre, which inhibited convective activity in that region, and contributed to the convectively asymmetric structure of the gyre. The gyre maintained a zonally persistent area of intense convection between 10° N and 20° N, which initiated genesis of a TC during the mature stage of the gyre.

From the description provided by MV2012 regarding the formation of the July 1988 subtropical gyre, it is clear that the gyre was a direct result of midlatitude forcing that in turn was influenced by the active MJO. Previously, a study by Moore et al. (2010) examined the mean state of the midlatitude westerly jet at 250 hPa during the boreal winter, where the mean location for the jet exit is approximately (35° N, 140° W), and equatorward wave breaking is maximized east of the jet exit region. Equatorward wave breaking has been known to foster the growth of precipitation in the subtropics, with the
development of deep convection most favored on the leading edge of the breaking wave (Funatsu and Waugh 2008). When the MJO was active over the Indian Ocean, Moore et al. (2010) noted that both the jet exit region and region of equatorward wave breaking retract westward in comparison to the climatological mean for December-February. Regarding the boreal summer, Tam and Li (2006) observed equatorward wave breaking occurring near the International Date Line that contributed to the development of low-level cyclonic disturbances. Postel and Hitchman (1999) found that peak equatorward wave breaking in the WNP occurs near the International Date Line from July-September, preferably downstream of upper-tropospheric subtropical high pressure systems. Furthermore, Ding et al. (2011) calculated climatological correlations between boreal summer mean heating over the Indian subcontinent and mean 200 hPa geopotential heights. They discovered that when a positive seasonal rainfall anomaly occurs over India, a midlatitude jet tends to develop over far northeastern Asia, creating an anomalous jet exit region over the northwest Pacific, and providing conditions favorable for equatorward wave breaking downstream. These works suggest that the relationships of the MJO, the midlatitude jet, and the equatorward wave breaking in boreal summer are dynamically comparable to the wave breaking events that occur during the winter months.

MV2012 establish a clear sequence of events regarding the formation of the 1988 subtropical gyre:

1. An active MJO over the Indian Ocean produced broad convection and resultant diabatic heating. The diabatic heating assisted in the development of a quasi-stationary upper tropospheric trough and jet exit region in the
northwestern Pacific Ocean, in agreement with the results of Ding et al. (2011).

2. The upper tropospheric trough produced a deep layer of northwesterly flow to its west, which enabled a series of midlatitude lower tropospheric lows to be carried equatorward as well as eastward.

3. The jet exit region was associated with multiple equatorward wave breaking events to its east (downstream), in agreement with Takaya and Nakamura (2001) and Moore et al. (2010). In particular, a wave breaking event that occurred from 19-22 July left behind a region of lower-tropospheric confluence near (20°N, 150°E), where the westerlies encountered trade wind easterlies. This resulted in midlatitude lows being unable to continue eastwards, and they stalled out in this area. Persistent convection arose within the confluent region.

4. As the gyre developed, a new midlatitude lower-tropospheric low moved equatorward, interacting and merging with an expanding area of lower tropospheric vorticity associated with the convection near (20°N, 150°E). It is stated that the large size of the gyre resulted from the broad region of cyclonic vorticity that evolved from this interaction.

5. The persistent convection described above produced a westward extension of the westerly winds, consistent with the solutions of Gill (1980) for steady convection north of the equator. These intensifying westerlies were accompanied by enhanced surface sensible and latent heat fluxes over the
warm WNP, and a subsequent westward expansion of the deep convection. The result of these events was a large, asymmetric cyclonic gyre.

6. A second wave breaking event occurred on 27-28 July. This created strong subsidence north of the mature gyre, accentuating the convective asymmetry that had already developed within the circulation.

The July 1988 subtropical gyre maintained cyclonic winds out to a radius of 2000 km, and obtained maximum winds at a radius of 700-800 km. The gyre displayed clear conditions at the center of the gyre (defined by MV2012 as the area of minimum pressure), and a strongly asymmetric convective signature, extending zonally some 4000 km within the southern flank of the gyre (and south of the center of circulation).

In discussion of the gyre, the authors weigh the role of ER waves on gyre development, expanding ideas first suggested in Molinari et al. (2007). While westward propagating waves were present upstream of the gyre, and would be likely to intensify in the confluent zone near 150°E and therefore promote gyre development, their findings show no evidence of vorticity maxima propagating from upstream flow. Midlatitude forcing appears to be the dominant factor in this case, with little evidence that Equatorial Rossby waves or any other westward-propagating wave played a major role in the actual buildup of the 1988 gyre.

In summarizing the previous literature, there are two crucial aspects of subtropical gyre analysis that are missing or deficient. One is that no previous study other than MV2012 has provided any quantitative measure of a gyre from gridded analyses. A formal gyre definition is lacking, and accounts for the wide differences in gyre frequency in the literature. Secondly, the role of surface fluxes has not been sufficiently considered,
and needs to be studied more thoroughly. MV2012 showed large fluxes in the convergence region equatorward of the gyre center. The relative importance of these fluxes during gyre formation has not been adequately addressed.

The current work will focus on a gyre that developed in the WNP in late July 1989. In the following section, an objective gyre definition for subtropical gyres is proposed, as well as a centering method to determine the location the gyre core. Further on, the analysis of the subtropical gyre is broken down into four parts, and utilizes multiple perspectives, such as potential vorticity, brightness temperature, and surface fluxes. The first subsection is a detailed analysis of the large-scale background environmental conditions before the existence of the gyre. The second subsection examines the WNP in the days immediately before the formation of the gyre, focusing on individual events in the region that played a role with the developing large-scale cyclonic circulation. The third subsection discusses the evolution of the mature subtropical gyre, providing an analysis of its movement and later evolutionary stages, as well as its vertical and horizontal structure and how those changed during the life of the gyre. The fourth subsection investigates the impact of the gyre, its influence on divergent circulations in the subtropical latitudes of the WNP, and its role in the development and movement of nearby tropical cyclones.
II. Data and Methodology

2.1 Gyre Definitions

One of the more pressing issues regarding the study of subtropical gyres in general is the lack of a clearly objective definition. The definition used by Lander (1994) and Holland (1995) is largely subjective, and there is no clear delineation as to when a large subtropical low is and is not a gyre. Although a mature gyre would be recognizable on satellite imagery based on the descriptions provided by Lander (1994), Lander specifically mentions intermediate configurations may be possible, but does not elaborate further. Disagreement over some of the stipulations concerning gyre magnitude, spatial coverage and temporal variation has further complicated the issue. An instance of this issue is the impact of gyres on TC development, with Chen et al. (2004) stating that approximately 70% of WNP tropical cyclogenesis is linked to subtropical gyres, while Ritchie and Holland (1999) attribute only 3% of all developing TCs in the WNP to the influences of subtropical gyres. Given this wide range, it is necessary to establish a clear, firm definition for when a subtropical gyre exists.

The definition proposed here relies on applying concrete and reproducible criteria:

1. The azimuthally-averaged circulation at 850 hPa must remain cyclonic at every radius (in 100 km bins) from the center to a radius of 2000 km. Because

\[
\bar{C} = 2\pi r \bar{v}_\lambda,
\]

this also means the averaged tangential wind speed at 850 hPa must remain positive for a radius of at least 2000 km.

2. The averaged tangential wind speed at 850 hPa must reach at least 8 m/s at some radius within the circulation.
The large size is designed to exclude smaller subtropical lows and tropical cyclones. The tangential wind requirement ensures that broad cyclonic regions, such as the monsoon trough, are omitted. This definition excludes any temporal requirement and instead defines the “lifespan” of the subtropical gyre as the time period where it fulfills both of the aforementioned requirements.

2.2 Calculations and data sources

Operational gridded analyses of 1.125° grid resolution from the European Center for Medium Range Weather Forecasting (ECMWF) available four times daily (0000, 0600, 1200 and 1800 UTC) were used to obtain values for the wind, height, and vorticity fields. Ocean surface flux calculations for 1989 were obtained from ECMWF ERA-Interim global atmospheric and surface model re-analyses (source website: www.ecmwf.int/products/data). The ocean surface fluxes are initially produced on a 0.7° latitude-longitude grid resolution (Simmons et al. 2007), but in data processing the resolution is reduced to a 1.5° latitude longitude-grid available twice daily (0000 UTC and 1200 UTC). Sea surface temperatures were taken from the NOAA optimum interpolation analysis (source website: http://www.esrl.noaa.gov/psd/). Time-averaged wind vectors and zonal wind anomaly fields at 200 hPa were obtained from NCEP/NCAR reanalyses (source website: http://www.esrl.noaa.gov/psd/data/composites/day/). WNP convective activity was evaluated using infrared (IR) brightness temperature data from the Cloud Archive User Service (CLAUS), available on a 0.5° latitude-longitude grid eight times daily. Tropical cyclone track and intensity data were obtained from the NOAA IBTrACS database (source website: http://www.ncdc.noaa.gov/oa/ibtracs/index.php?name=ibtracs-data). The
IBTrACS data set includes both JTWC (The U.S. Navy Joint Typhoon Warning Center) data and JMA (Japanese Meteorological Agency) data. JMA data was used for all TCs that reached tropical storm strength or greater (identified as 35 knots or greater in IBTrACS). JMA does not track storms weaker than that intensity, and as a result track and intensity information for tropical depressions was taken from the JTWC. Three-hourly satellite imagery for the event is supplied by the JMA GMS-3 satellite, using visible wavelength (0.6 µm) for the daytime periods of 0000 UTC - 0900 UTC, and infrared (11 µm) for the nighttime imagery of 1200 UTC - 2100 UTC. These images were downloaded from the NOAA GIBBS satellite imagery archive (source website: http://www.ncdc.noaa.gov/gibbs/calendar/1989).

In this work, one of the methods used in elucidating the impacts of the subtropical gyre is time-averaged velocity potential and divergent wind at 200 hPa. These are useful in measuring the amount of outflow coming from the upper-levels above the gyre circulation, and their impacts on other large-scale disturbances extending beyond the WNP. An explanation of the application of divergent wind and velocity potential is supplied here.

Following the Helmholtz theorem, the total wind can be divided into two unique parts:

\[ \mathbf{V} = \mathbf{V}_\psi + \mathbf{V}_x \]

Where the first part, \( \mathbf{V}_\psi \), represents the purely rotational component of the wind (has no divergence), and the second part, \( \mathbf{V}_x \), represents the purely divergent component of the
wind (has no vorticity). The divergent wind can be expressed in terms of velocity potential ($\chi$) via the horizontal gradient of the velocity potential field:

\[ V_\chi = -\nabla h \chi \]  

In this setup, $V_\chi$ is perpendicular to lines of velocity potential, and proportional to the gradient of velocity potential. The benefit of adding the minus sign and reversing the integer value is that it allows air flow to be displayed as flowing out of velocity potential maxima, which is more intuitive. Furthermore, horizontal divergence, D, can be explained in terms of both divergent wind and velocity potential:

\[ D = \nabla \cdot V = \nabla \cdot V_\chi = \nabla \cdot (-\nabla h \chi) = -\nabla^2 \chi \]  

Physically, this indicates that in the case of a velocity potential maximum, $\nabla^2 \chi < 0$ at a maximum and therefore $D = -\nabla^2 \chi$ is $> 0$, meaning that positive divergence is observed at a $\chi$ maximum.

2.3 Gyre Centering

Determining the center of the gyre has proven critical to understanding gyre evolution. Previously, in Lander (1994) and more specifically, in MV2012, the center of circulation was determined to be the grid point with the lowest pressure within the gyre cyclonic circulation. However, this posed problems in this study. TCs that develop in the peripheral convection of the gyre may obtain minimum sea level pressures that are lower than that of the gyre circulation. Therefore, a centering algorithm designed to track the minimum pressure would focus on the TC rather than the center of the gyre circulation itself. In previous work, this was not a major issue, but only because the 1988 gyre
examined by MV2012 produced only one TC very late in its life span, beyond the time of interest in their study. However, in the 1989 subtropical gyre case that is the focus of this work, TCs are present throughout the life span of the gyre, and as a result pose a serious hazard in trying to accurately determine the coordinates of the center of the gyre.

Given the issues with the minimum pressure method, a new approach was established. Instead of concentrating on the minimum pressure, an algorithm is applied to an ECMWF latitude-longitude grid of 1.125° x 1.125° resolution. At each point in the grid, the azimuthally averaged circulation at the 850mb level is calculated for all radii (100 km intervals) from 900-1200 km. The 900-1200 km value is selected because smaller radii would allow the possibility of data contamination by large TCs, while values larger than 1200 km tend to take into account extraneous larger-scale features outside of the gyre circulation, such as easterly trade winds near the equator. The grid point with the highest average circulation is selected as the subtropical gyre center. In Fig. 1, the location of the calculated center of circulation is plotted in the visible satellite imagery for the first three days where the gyre met the definition criteria, and shows that this center is separate from the regions of active convection.

In the section regarding gyre interactions with nearby TCs, it is necessary to smooth the track, as the unsmoothed track is locked onto the grid points in the data, and results in an unrealistic assessment. A smoothing script is then applied, weighted such that the final value is a 1-2-1 average of the latitude and longitude values. This interpolated location of the maximum value for the azimuthally averaged 900-1200 km circulation is considered to be the center of the gyre for a given time period. These interpolated values are used only in the analysis of gyre impacts on nearby TCs.
III. The July 1989 Subtropical Gyre

3.1 Large-scale Background and Environment

In order to fully understand the formation of the subtropical gyre, it is necessary to put its development and evolution in proper environmental context. Fig. 2 shows Hovmöller diagrams of unfiltered 850 hPa zonal wind and the infrared brightness temperature ($T_b$), averaged over two latitude bands, one from 6°N -16°N and the other from 16° N -26° N. These latitude bands were selected based on the subtropical gyre initially meeting the working definition when the center of circulation was located at approximately 26° N, and the gyre location is marked by a black asterisk in Fig. 2b. Fig. 2a, the zonal wind band from 6° N-16° N, shows a sudden increase in the extent of westerly winds starting around 15 July, with the westerlies undergoing a substantial expansion from about 95° E-125° E to 110° E – 135° E. This can be attributed to the eastward propagation of the MJO. The easterlies in the easternmost portions of the figure represent the trade winds. The existence of multiple westward-propagating disturbances is readily apparent, with a period of about 8 days. These are most likely Equatorial Rossby waves, which modulate the expanding envelope of westerlies associated with the MJO.

Examining the interval from 16° N-26° N (Fig. 2b) casts a somewhat different picture. Before 25 July, westerlies rarely extend past 110°E, but a developing TC near 140° W, TY Judy, produces an eastward extension of the westerlies as they provide low-level inflow into the TC. This extension persists from 24 July – 6 August, first as inflow for TY Judy, and then maintained by the formation of the subtropical gyre, where the
extended westerlies are the result of being in the southern flank of the large cyclonic circulation of the gyre. As the gyre moves northwestward, the westerlies are linked to extended low-level inflow with a TC, this time TY Mac. This flow persists until the TC moves into the extratropics, severing the link. Without disturbances to sustain their presence, the westerlies quickly return to their pre-gyre longitudinal bounds.

Examining the brightness temperature Hovmöller diagrams for 6° N-16° N and 16° N-26° N (Figs. 2c and 2d respectively) shows westward-propagating waves interspersed with convectively active and inactive periods in both latitude intervals. The broad convection associated with the equatorward side of the gyre is readily apparent in Fig. 1d in the form of a sudden increase in convection east of 120° E during late July and early August. In the 6° N-16° N band interval (Fig. 2c), the westward-propagating waves match up well with the strengthened westerlies over 70° E–90° E, suggesting an enhancement of monsoon southwesterlies as the wave passes through. However, for the 16° N-26° N latitude band (Fig. 2d), the last large westward-moving disturbance passes through the gyre region several days prior to the sudden expansion of the westerlies.

From these images, it appears that if equatorial waves are involved in the development of the gyre, it would be an indirect component, because the gyre develops near 26° N but the strong westerlies lay equatorward of 16° N.

However, other environmental features play a stronger role in the formation of the gyre. Fig. 3 shows the averaged SSTs for the WNP from 6 July – 26 July, the three weeks leading up to the gyre. The area where the center of the gyre circulation developed is shown by the grey “L”. The center lies in an area of SSTs of 302.5 K (29.5° C), and these temperatures are the result of boreal summer condition as well as a La Niña, when
warm waters tend to extend further poleward (Wang and Chan 2002). The 302 K SST values extend up to 25° N – 30° N and eastwards to 165° E at the equator, with a weak cooling to the east and a rapid cooling to the north.

Fig. 4 shows a Hovmöller diagram of the unfiltered 200 hPa zonal wind, averaged over 30° N - 40° N for 1 June – 15 August 1989. It is clear in this figure that until about 20 July, the westerly zonal winds were quite strong, indicative of a significant jet stream in the region. However, after 20 July, the winds become much weaker, and the jet stream is suddenly absent from the 30° N - 40° N latitude band. An examination of the 200 hPa wind speeds over the WNP averaged from 15 July – 25 July (Fig. 5) shows that west of 130° E, the jet stream has shifted northward, and for a region spanning 130° E to 155° E, the jet has broken down, with winds averaging less than 20 m s\(^{-1}\) in that longitude band. These abrupt changes create a jet exit region over northeastern Asia and the Yellow Sea.

Fig. 6 shows vector wind anomalies with shaded zonal wind anomalies. The zonal winds at approximately 45° N over northern Asia (90° E – 120° E) are stronger than normal by 15 m s\(^{-1}\) or greater, while the zonal winds for the same latitude over Japan and the WNP (130° E – 170° E) are anomalously weak by over 15 m s\(^{-1}\). These zonal wind anomalies indicate a more prominent jet exit region for northeastern Asia in comparison to the climatological mean configuration.

In consideration of the 200 hPa mean wind fields (Fig. 5) and the anomalies from climatology (Fig. 6), there is a strong possibility that the MJO is involved. Fig. 7 displays a Hovmöller diagram of OLR averaged 7.5°-17.5° N from 1 June to 15 August 1989. The OLR field is unfiltered, except for the removal of the seasonal cycle. Cool colors indicate cold cloud tops (high clouds) and strongly correlate with precipitation. Also shown in
Fig. 7 are contours of MJO-filtered OLR. The diagram is generated from the time-extended EOF analysis of Roundy and Schreck (2009). Notably, the MJO over the Indian subcontinent (90° E) was inactive from late June to mid-July 1989. It was then quickly followed by an active phase that reached 90° E by 20 July and propagated eastward to about 135° E by the end of the month, when its convective signal faded. The black asterisk in Fig. 7 shows the location of the subtropical gyre when it first met the definition criteria at 1200 UTC 28 July. The 1989 subtropical gyre formed on leading edge of the MJO, just before the decay of the convective signal of the active MJO. The results of Fig. 7 are consistent with the winds shown in Fig. 2a.

3.2 The Formation of the Subtropical Gyre

3.2.1 Formation from a PV Perspective

The formation of the subtropical gyre is a complex process that occurs over a period of several days, with several elements, both tropical and extratropical in origin, playing a crucial role. The gyre formation process involves a series of events that occurred during 24-29 July 1989.

Fig. 8 details a sequence of once-daily weather maps from 1200 UTC 24 July to 1200 UTC 29 July. Examined features in these images include Ertel potential vorticity (PV) in the upper troposphere (350 K isentropic surface), along with 850 hPa wind vectors and contoured 850 hPa cyclonic relative vorticity. On 24 July (Fig. 8a), an extended area of upper-level positive PV stretches from Japan into the subtropics, indicative of a mid-latitude upper-level trough, while further east, a large region of low-level vorticity, labeled “J”, shows the low-level vorticity signature of a developing TC,
Tropical Storm (TS) Judy, centered at 18.9° N, 138.2° W. An area of low-level vorticity, vorticity maximum “A”, develops directly in association with the upper-level trough. The following day (1200 UTC 25 July, Fig. 8b), “A” has begun to merge into the developing TC, now a typhoon (TY), while a new vorticity maximum, referred to as “B”, develops near 21° N, 126° E. The upper-level trough has become elongated, in the process of undergoing equatorward wave-breaking. One important detail in this image is that the 850 hPa winds are westerly west of B, and given this low-level flow, “B” may have formed further west and moved east, where it then encountered the upper-level trough.

By 1200 UTC 26 July (Fig. 8c), the upper-tropospheric anticyclonic wave-breaking process is complete, and an upper-level cutoff low is now deposited into the WNP, roughly centered at 23° N, 129° E. “A” has lost its unique identity as it completes its merger into the growing TC represented by vorticity region “J”. On the other hand, “B” has continued to develop, its low-level cyclonic vorticity increasing in magnitude as it moves closer to the center of the upper-level cyclone. In previous literature (e.g. Sippel et al. (2006)), it has been described that PV superposition can play a role in low-level cyclogenesis, by establishing an environment of decreased vertical shear and increased instability that can enhance the development of nearby MCSs. So it is likely that vorticity maximum “B” is benefitting from the presence of the cut-off low, and becoming stronger as a result of the interaction.

Moving ahead one day (1200 UTC 27 July, Fig. 8d) shows that “B” has continued to strengthen as it moves in a cyclonic orbit around the upper-level low, represented by the positive PV anomaly. Where “B” first began to engage with the upper-level low, a new vorticity maximum, “C”, has developed. By 1200 UTC 28 July (Fig. 8e), the gyre
criteria have been met, with the 900-1200 km azimuthally-averaged center of circulation located at 26.25° N, 127.75° E. Another key aspect of this image is that the mid-latitude trough that participated in the anticyclonic wave-breaking event, and had been moving eastward, has now begun to retrograde. To take a closer look at the cause of this retrograde motion, a large-scale image of PV and 850 hPa cyclonic vorticity contours was used (Fig. 9), with the substitution of wind vectors at 350 K to indicate the upper-level flow. The image shows an area of weaker PV pushing poleward to latitudes greater than 50° N, likely the result of diabatic ridging, which may have been enhanced by the poleward movement of TY Judy. As part of the upper-level anticyclonic circulation, the trough, on the eastward and equatorward side of the ridge, is pushed west by the upper-level flow, resulting in a retrograde westward motion.

The final panel of Fig. 8, for the mature gyre at 1200 UTC 29 July 1989, shows that the gyre has moved south-southeastward. The rapid southward movement is likely a result of the calculation mechanism for the center, with the culprit being TY Judy. The previous day, the TC maintained a substantial area of cyclonic vorticity in range of the 900-1200 km azimuthal averaging for the circulation, skewing the values away from vorticity maxima “B”, “C” and “D”. When the TC continued to move poleward (by 29 July, it is weakening and undergoing extratropical transition (JTWC 1989)), it moved out of the range of the azimuthal averaging, so the center “jumped” equatorward, back to between the vorticity maxima that most directly played a role in the development of the gyre. Since the gyre structure is influenced by multiple moving disturbances, there does not appear to be a method that prevents occasional shifts in position, like that shown in Fig. 8f. Another key part of this figure is that the upper-level trough is undergoing a
second wave-breaking event, which will play an important role in the evolution of the subtropical gyre, to be discussed further in the section 3.3.

3.2.2 Formation from a Brightness Temperature Perspective

In order to examine several aspects of the gyre development at once, it is necessary to look at the same time periods, but with different variables. In this section, CLAUS brightness temperatures, which indicate the temperature of cloud-tops and can be used to identify the intensity and spatial spread of convection, are used in place of PV. Fig. 10 displays brightness temperature once daily at 1200 UTC for 24-29 July 1989, as previously done with the PV in Fig. 8. The 850 hPa cyclonic vorticity contours and 850 hPa wind vectors are maintained, and allow for easy comparison to Fig. 8.

Starting at 1200 UTC 24 July 1989 (Fig. 10a), the majority of the convection in the WNP is with the developing TC, and no convection appears with vorticity maximum “A”, which is directly associated with the upper-level midlatitude trough penetrating into the subtropics (Fig. 8a). Sporadic, weak to moderate convection exists east of “A” (and the trough). One day later (1200 UTC 25 July, Fig. 10b), the convection has become somewhat more widespread, particularly in the region of developing vorticity maximum “B”. In six-hour analysis (not-shown) “B” appears to have developed from the merger of two smaller vorticity maxima that formed further west and away from the trough; one of these maxima can be seen in Fig. 10a over the northern Philippines. This suggests that unlike “A”, “B” was not directly associated with of the upper-level trough.

The CLAUS image for 1200 UTC 26 July (Fig. 10c) shows that the area of convection associated with vorticity maximum “B” has become slightly larger and better
developed. Perhaps as a result of this development, “B” shows increasing cyclonic vorticity. Also of importance is the trailing convection extending eastward and equatorward from the TC, in an area of confluent low-level winds. Over the following day, the TC separates from this trailing convection, and the trailing area breaks down into a chain of convective regions, as seen on 27 July (Fig. 10d). These areas of convection become important in establishing the eastward and equatorward convection of the subtropical gyre, and this may be the most important role that TY Judy plays in the development of the gyre. Meanwhile, “B” has continued to move cyclonically around the upper-level low (Fig. 8d), but is relatively devoid of convection, with only sparse, weak activity in the vicinity of the vorticity maximum. Although it is suggested that “B” is increasing in magnitude, the lack of convection suggests there may be an overestimation of vorticity within the ERA-Interim reanalysis data. Where “B” first engaged with the upper-level low, a new vorticity maximum, “C”, has formed, embedded within the roughly zonal band of convection near 20° N.

By the time the gyre first meets the definition criteria (1200 UTC 28 July, Fig. 10e), the area of cloud tops to the south of the gyre has increased in size, filling in the zonal band to create a wide, roughly continuous line of convection from 120° E to 150° E. A meridional band is in place around 145° E, outside of the initial gyre circulation. “B” still lacks significant convection as it continues its cyclonic orbit, and “C” has moved around the upper-level low but remains entrenched within the convective band on the equatorward side of the gyre. A new vorticity maximum, “D”, has formed close to where “C” had developed, but unlike “C”, it fails to maintain itself and breaks down by the following day.
The last time period in the set shows the distinct convective arrangement of the mature gyre (1200 UTC 29 July, Fig. 10f). A clearly defined zonal band exists equatorward from the center, and the convection further east has begun to move westward towards the center of circulation, perhaps as a result of the easterly low-level winds and westward moving upper-level trough. Vorticity maximum “E” develops adjacent to this meridional band. Closer to the gyre center, “C” has begun moving poleward in its cyclonic orbit within the circulation, but appears to be maintaining some convection on its equatorward side. Vorticity maximum “B” has been able to trigger and sustain some convection, enough to be declared a tropical depression (TD 12W) by the JTWC six hours previously (JTWC 1989). At this point, it has been clearly established that the development of convection occurred rapidly over a few days, forming a well-defined zonal band, and a meridional band to the east that was outside of the initial gyre circulation.

3.2.3 Formation from a Surface Heat Flux Perspective

A third aspect involved in the formation of the subtropical gyre involves the role of surface fluxes into the atmosphere. For the development of prolonged, deep convection, an unstable atmosphere is important, but so are significant surface fluxes. Surface fluxes can provide an energy influx into the atmosphere, which may result in a more unstable environment and enhanced convective activity. This is important for establishing and sustaining the large convective band of the gyre. Through diabatic heating within the convection, fluxes contribute to the maintenance of the vorticity maxima. Therefore, it is important to identify the role and evolution of oceanic surface heat fluxes as the gyre coalesced.
Fig. 11 examines oceanic surface latent heat fluxes over the WNP. Here, positive values indicate energy transfer from the ocean into the atmosphere, with hatching and cross-hatching used to describe areas of larger heat fluxes. CLAUS brightness temperatures are once again used in order to link fluxes to active convection, and surface wind vectors are also plotted for the time series of images. To allow for simple comparisons to the previously examined time series, the imagery shows once daily plots for 1200 UTC 24-29 July 1989.

In allowing the establishment of a benchmark for “normal” values it is necessary to conduct a review of work previously done on latent heat energy transfer in the WNP. On a broader timescale, Weare et al. (1981) compiled an annual average of energy transfer over the Pacific Ocean from 1957-1976, and found values in the gyre formation region averaging in the range of 150-200 W m$^{-2}$, stating that latent heat flux values are generally higher in the cool season. An analysis of latent heat flux by Chou et al. (1995) for August 1988, a boreal summer month that, like July 1989, was also during a La Niña, found values in the 80-120 W m$^{-2}$ range. Given these values, it seems reasonable that the hatched 175 W m$^{-2}$ values could be described as “above average”, and the 275 W m$^{-2}$ or greater cross-hatched regions as “well above average” for the WNP in July 1989. It is to be expected that regions of higher heat fluxes are strongly correlated to areas of intense convection; as convection develops and diabatic heating takes place, hypsometric reasoning suggests that surface pressure should decrease. Assuming the outermost isobar remains constant, as surface pressure decreases, the pressure gradient increases. This increases the magnitude of the surface winds, which in turn allow for greater energy transfer into the atmosphere, and more energy to foster the growth of convection.
Therefore, convection and oceanic latent heat fluxes may engage in a positive feedback mechanism, and often appear concurrently.

The initial image, for 1200 UTC 24 July (Fig. 11a), shows values greater than 175 W m\(^{-2}\) in the vicinity of developing TY Judy, and in scattered regions further east. It is likely that there may be localized areas of higher values within the TC that are not identifiable due to the resolution of the data. Surface winds in the region of gyre formation are generally weak. The next day (1200 UTC 25 July, Fig. 11b), a small area of high heat fluxes can be seen north of the Philippines, likely playing a role in the convective region developing with vorticity maximum “B”. What stands out most, however, is the presence of a SW-NE oriented band of higher latent heat fluxes extending through the elongated tail of convection of TY Judy. Fluxes are enhanced in this region of extended convection as a result of the enhancement of the southwesterly winds.

By 1200 UTC 26 July (Fig. 11c), multiple areas of higher heat flux coincide with developing vorticity maximum “B”, and include patches left over from the breakdown of the extended line of convection from TY Judy. In this regard, the typhoon can be said to have formed the seeds for the extended zonal region of convection. As convection starts to become more widespread at 1200 UTC 27 July (Fig. 11d), areas of higher heat fluxes persist near 20° N, close to developing vorticity maxima. A larger region of high heat fluxes to the northeast, along with the easterly surface winds, may be helping to drive development of the meridionally-oriented branch of convection developing near 145° E. As the gyre first meets the definition criteria at 1200 UTC 28 July (Fig. 11e), the individual high heat flux regions have become more widespread, merging into one larger heat flux region and sustaining the equatorward convection of the subtropical gyre.
through increased positive surface forcing. By the time of the mature gyre (1200 UTC 29 July, Fig. 11f), an extensive region of surface fluxes continues to provide energy to the equatorward convection, with some surface flux values peaking at over 275 W m$^{-2}$. It is clear that as the convection grew, so did the size and intensity of the high surface latent heat fluxes, and by the end of the time period, there are large heat fluxes and convective regions over a wide area of the gyre.

3.2.4 The Expansion of the Cyclonic Circulation

While it is imperative to analyze the development of the subtropical gyre from the piece-by-piece framework of convective regions and vorticity maxima, it is also important to examine the gyre-scale evolution and how it changed during the formation period. Fig. 12 shows a plot of averaged circulation from 900-1200 km radii at 850 hPa. This is calculated separately at each grid point before plotting. The images are once daily at 1200 UTC for 25-29 July 1989, covering the period before, during, and immediately after the time of formation. On 25 July (Fig. 12a), two circulation maxima are evident in the WNP, and both of these have strengthened by 1200 UTC 26 July (Fig. 12b). As we see them coalesce into one circulation maximum by 1200 UTC 27 July (Fig. 12c), it is also apparent that an additional area of cyclonic vorticity continues to grow and intensify near 150° E, expanding the envelope of cyclonic circulation about 10° eastward. By the time of gyre formation (1200 UTC 28 July, Fig. 12d), the maximum circulation has actually weakened slightly, but the region of cyclonic circulation has broadened, and this persists into the mature gyre phase (1200 UTC 29 July, Fig. 12e). This eastern feature that contributes to the expansion of circulation seems to be the product of the diffuse region of convection and weak cyclonic vorticity eastward of the gyre development.
region, as seen in Fig. 10f. The eastward expansion of the cyclonic circulation as shown in Fig. 12 could be an indication of the MJO propagating eastward.

Each set of imagery shown here gives important information regarding the development of the subtropical gyre. Through PV imagery, a direct role can be seen of the extratropics in the development of the July 1989 gyre. The extended midlatitude, upper-level trough underwent an anticyclonic wave-breaking event that deposited a cut-off low in the subtropics. This became the common center for the multiple vorticity maxima that developed in the region, and helped define the low-level cyclonic circulation of the subtropical gyre. The upper-level low also may have created a more unstable atmosphere, allowing for more significant production of convection in the region. Furthermore, as seen through the brightness temperature and the surface latent heat flux plots, the presence of large amounts of convection promoted the growth of the low-level vorticity maxima, which intensified and increased in number, permitting the formation of the subtropical gyre. Through the gridded circulation plots, it is demonstrated that multiple features both near and far from the gyre center exerted influence on the developing subtropical gyre. The circulation was not only influenced by features in the immediate vicinity of the developing gyre, but by other disturbances in the WNP, such as a region of scattered convection and positive vorticity further east that expanded the region of cyclonic circulation.

3.3 Gyre Structure and Evolution

3.3.1 Evolution of the Circulation and Tangential Wind
To analyze how the subtropical gyre changed during its six-day lifespan, it is necessary to look at the evolution of its internal structure, as well as its movement and interaction with the surrounding environment in the WNP. Fig. 13 displays azimuthally-averaged tangential wind speed with respect to the gyre center (Fig. 13a), and azimuthally-averaged circulation (Fig. 13b). The plots are produced once daily at 1200 UTC for 27-30 July 1989, which allows for an analysis of wind speed and circulation just prior to the gyre meeting the definition, as well as the first couple days after formation.

One of the more prominent attributes of the subtropical gyre is that the buildup of the tangential winds and cyclonic circulation were not sudden. In comparing the gyre flow from 1200 UTC 27 July to 1200 UTC 28 July, the innermost 400 km of the tangential winds shifted from anticyclonic at less than 1 m s\(^{-1}\) cyclonic and above 2 m s\(^{-1}\), and concurrently, the azimuthally-averaged circulation in this region went from very weakly negative to very weakly positive. Although the possibility exists that the definition would be met for transient periods before 28 July, analysis of the 6-hourly data shows that the 1200 UTC time was the first period the gyre was fully cyclonic for the entire span of its radius. The 8 m s\(^{-1}\) maximum tangential wind speed criterion is met for all time periods, and stays fairly constant between 11 and 13 m s\(^{-1}\).

Fig. 14 is the same as the previous figure, but for 1200 UTC 31 July – 1200 UTC 3 August 1989, the mature and decaying phases of the gyre. The azimuthally-averaged tangential wind peaks at just under 16 m s\(^{-1}\) at 700 km out from the center on 31 July, and then decreases and holds steady for the following two days, before dropping and dipping negative (anticyclonic) near the center at 1200 UTC 3 August. Further analysis indicates
that 0600 UTC 3 August was the last time period the gyre met the definition criteria.
Over the same three-day period, the cyclonic circulation weakens and peaks further out with each successive time period, before quickly decreasing at the periphery at the 3 August post-gyre period. These circulation and tangential wind vs. radius plots serve as indicators of how various features, both close and further from the center of circulation, impact the mature gyre structure, and these will be explored further in the following subsections.

3.3.2 Evolution from a PV Perspective

To adequately assess the movement of the gyre and its interaction with features in or near its circulation, it is necessary to return to PV-based analysis. Fig. 15 is as before in Fig. 8, but once daily at 1200 UTC for 30 July – 2 August 1989. At 1200 UTC 30 July, the second wave-breaking event associated with the mid-latitude upper-level trough is complete, with an upper-tropospheric cutoff low located northeast of the gyre center. Vorticity maximum “B”, associated with the decaying TD 12W, remains on the western periphery of the gyre circulation, and lingers in this region for the next few days. Vorticity maximum “C”, now recognized as a TC, comprises the only strong area of vorticity near the gyre center, encompassing much of the eastern half of the circulation, and located due east of the upper-level cutoff low. Much further east near 150° E is a large area of cyclonic vorticity, labeled “M”. “M” develops into a TC (TY Mac), but remains on the outer edge of the gyre circulation. The role of “M” will be discussed further in section 3.3.5.
On 31 July (Fig. 15b), two new vorticity maxima have developed east and southeast of the gyre center—“F” and “G”, respectively. These two maxima are moving cyclonically and poleward at a location several degrees further east than when “B” began the poleward portion of its orbit, and this adjustment may be the result of the eastward shift of the gyre and caused by the second equatorward wave-breaking event. Meanwhile, “C” has continued in its cyclonic orbit around the gyre, and is the most responsible for inward shift of the tangential wind magnitude as seen on the azimuthally-averaged wind vs. radii plots in Fig. 14a. The gyre center has shifted a few degrees east to 25°N, 132°E, the result of the influence of “F” and “G”.

By the following day (1 August, Fig. 15c), “C” is almost stationary. Vorticity maximum “G” has dissipated, but “F” has persisted, moving cyclonically around the gyre and lying north-northeast of center. With the removal of “G” and movement of “F”, the gyre center has adjusted northward. At 1200 UTC 2 August, the last day shown here (Fig. 15d), “F” has largely dissipated (the weak maximum near 35°N, 130°E is a separate development), and “C” is the only major player in determining the gyre circulation, with the center lying close to the maximum within “C” and the TC it is associated with. This is supported by the previous figure, which shows the closeness and intensity of the maximum winds to the gyre center on 2 August. As the TC moves westward and into the Asian continent over the following day, the gyre is left with no major vorticity maxima nearby and the circulation decreases, and no longer meets the gyre definition after 0600 UTC 3 August. It is only on this last day that the upper cutoff low has substantially weakened, demonstrating the persistence the mid-latitude forcing throughout the event. Through PV analysis it is shown that the extratropics did not just impact the formation of
the subtropical gyre, but its evolution as well, pushing it eastward and broadening the locations of the maxima that help defined the gyre.

3.3.3 Evolution from a Brightness Temperature Perspective

Giving due consideration to CLAUS modeled brightness temperature for the mature subtropical gyre is essential to deepen our understanding of the evolution of the system. Fig. 16 is as before in Fig. 9, but for the times in Fig. 15. At 1200 UTC 30 July (Fig. 16a), the characteristic asymmetric convective signature of the mature subtropical gyre is evident, with clearly developed equatorward and eastward flanks. The gyre center is in an area clear of convection just north of the equatorward flank. However, 24 hours later (1200 UTC 31 July, Fig. 16b), the convection northeast of the gyre center has largely dissipated, with a small area of persistent convection associated with vorticity maximum “C”, and most of the intense convection relegated to south or southeast of the gyre center. In the cases of both “F” and “G”, the convection is displaced equatorward of the vorticity maximum. Through the extended zonally-oriented convection, it is shown that the gyre convection is adjoined to the convection associated with vorticity maximum “M”, which is still developing into a TC.

Over the time periods of 1 August and 2 August (Figs. 16c and 16d), the zonal band of gyre convection becomes absorbed into the overall circulation of “M”, forming an elongated convective band over 20° longitude that extends into the core of the growing TC. “F” quickly loses its convection as it moves poleward and weakens, and the gyre is largely devoid of convection by the final frame, the only intense region left being the resurgent cold cloud-tops associated with “C”, now a strong tropical storm (JTWC 1989).
From this image, the conclusion could be drawn that the mature convective state of the gyre is short lived, possibly due to the burgeoning TC to its east. However, the overall structure is still suggestive of an MJO signal marching eastward.

3.3.4 Evolution of the Internal Structure

Lastly, while it is important to understand the motions of the gyre and its interactions with neighboring features, it is crucial to get an idea of its internal composition, such as the depth of its warm core and the structure of the vertical wind field. Fig. 17 looks at the wind field throughout the depth of the gyre, and out to a radius of 2000 km, in line with the working definition. Figs. 17a, 17b, and 17c look at the zonal wind from south to north at 1200 UTC on 29 July, 31 July and 2 August, while Figs. 17d, 17e, and 17f examine the meridional wind from west to east for those same time periods.

In examination of the zonal wind structure, the cyclonic structure of the subtropical gyre is readily apparent, with strong westerlies located south of the center, and strong easterlies located to the north. The maximum wind speeds associated with the gyre are generally located around 800 hPa, although in Fig. 17a (1200 UTC 29 July) the strongest westerlies are a little higher at about 700 hPa. These maxima occur closer to the center in the equatorward flank (200-600 km) versus the easterlies on the poleward side (500-800 km). The zonal wind structure in all three periods is pronounced and quite deep, extending the surface and into the upper troposphere above 300 hPa.

The case for the meridional winds is more convoluted. Fig. 17d (1200 UTC 29 July) presents a confusing picture of strong southerlies east of the center (as would be expected in a cyclonic circulation), but weak northerlies over the center, and modest
southerlies west of the center. These structures are all fairly deep, dissipating above 200 hPa. The reason for this unorthodox image is that, when looking at the winds in the PV and CLAUS imagery (Figs. 9f and 10f), vorticity maximum “B” was in this region, and since the western flank of the gyre did not develop as quickly as the other regions and the gyre winds were weaker, the winds from “B” were not counteracted by the gyre. The southerlies shown are likely part of the cyclonic circulation of “B”. With “B” moving out of the cross-section by 1200 UTC 31 July (Fig. 17e), a more orderly cyclonic rotation is seen. The maximum northerlies are at the 500 hPa pressure level and 600 km west of the center, while the maximum southerlies are on a different level, 800 hPa and 1000 km east of the center. Even in the final time period (1200 UTC 2 August, Fig. 17f), although the winds indicate a cyclonic circulation at 800 hPa, with the low-level winds peaking at 250 km east and 600 km west of the center, a second set of stronger cyclonic winds exists in the upper troposphere, centered 800 km west of the lower-level center. This is likely the result of vorticity maximum “C” (Fig. 15d). In all the cases, the circulation is deep (surface to 200 hPa or above), and the winds are generally weaker when compared to their zonal counterparts. As an aside, the strong winds well to the east are likely associated with the structure of “M”.

Looking at another aspect of vertical structure, Fig. 18 examines the vertical profile of the relative vorticity within the subtropical gyre, at the same periods analyzed in Figs. 16 and 17. It is established in Fig. 18a that early in the life of the gyre (1200 UTC 29 July, Fig. 18a), the maximum vorticity is near the center and in the low-levels, indicative of a warm-core cyclone. However, the following time period (1200 UTC 31 July, Fig. 18b) indicates a strong cyclonic vorticity maximum at 300 hPa, about 500 km
north of the gyre center. In comparison with the PV imagery in Fig. 15b, this is likely a result of the upper-level low deposited by the second equatorward wave-breaking event. The last time period (1200 UTC 2 August, Fig. 18c) shows a cyclonic maximum at 800 hPa tapering off slowly with height.

These cross-sections paint a picture where the cyclonic circulation on the north and south sides of the subtropical gyre are well-defined, but the east, and in particular the west, are not as pronounced. Although in most images there is a peak in the winds and vorticity at low level similar to TCs (Hawkins and Imbembo 1976), the scale of the structure and the evidence of strong winds aloft indicate a feature that is not purely tropical. The images suggest the gyre structure transitions from weakly cool-core to warm-core in the last time period. Also, the influence of the extratropics should not be understated, as it is quite visible with the depth of the positive vorticity in Fig. 18b; upper-level lows exhibit a vorticity maximum aloft, and the low is playing a major role in the vertical structure of the gyre.

3.3.5 Dual Circulation Centers of the Subtropical Gyre

In examination of the life of the gyre, there is some ambiguity with what is and is not the subtropical gyre. As a solitary area of cyclonic vorticity, “M” plays only a minor role in the evolution of the gyre (that being the additional cyclonic vorticity from the TC enhancing the circulation at the outermost eastern radii). However, an examination of the gridded circulation of the averaged 900-1200 km radius reveals a new facet of “M” and its relation to gyre development. Fig. 19 examines the daily gridded circulation as before in Fig. 12, but for 1200 UTC 30 July – 1200 UTC 3 August 1989. In Fig. 19a, it is shown
that the gyre is the primary cyclonic circulation in the WNP, extending out to about 150° W. A small, weak region of cyclonic circulations lies further east. By 31 July (Fig. 19b), this region has consolidated into the main circulation, and a secondary circulation develops near 145° W, between the gyre and “M”. The following day (1200 UTC 1 August, Fig. 19c), the secondary cyclonic circulation continues to strengthen, consisting of two small regions of higher circulation developing between 140° and 150° N. During these three periods, the subtropical gyre circulation to the west has remained substantially stronger than the eastern circulation, and lies relatively stationary, just east of 130° N.

However, by 2 August, (Fig. 19d), the circulation of the eastern center grows in strength as the subtropical gyre circulation begins to weaken. The shift is complete by the last time period (1200 UTC 3 August, Fig. 19e), with the gyre circulation now weaker than the eastern circulation, which is stronger than the gyre circulation was in any previous time period. This eastward shift of maximum cyclonic circulation could be interpreted as the MJO signal propagating eastward, in accord with Fig. 16.

Previously, work by Chen et al. (2004) has suggested that “M” and this eastern circulation (collectively referred to as the eastern disturbance) are part of the July 1989 gyre. Its development is noticeably different from the western circulation center, with the dominant influence being the area where vorticity maximum “M” develops (near 150° W, Figs. 15 and 16), rather than an agglomeration of vorticity maxima. “M” develops into TY Mac, growing as the cyclonic center of the gyre weakens. For 18 hours (0000 UTC 4 August – 1800 UTC 4 August), this eastern disturbance actually meets the definition of a subtropical gyre as described here, and satellite imagery suggests a gyre-like asymmetric convective signature, as seen in the later images of Figs. 1c, 1d and 16d.
However, while it has been proposed as a part of the 1989 subtropical gyre, there is one issue with such an argument. As shown in Fig. 19, while it maintains one continuous cyclonic structure continuous with the western gyre, the two distinct circulation centers are 15° apart from each other, with the eastern circulation maximum rapidly developing after 1200 UTC 1 August (Fig. 19c). The location of the eastern maximum slightly west of “M” is likely the result of vorticity maxima in the gyre. Rather than treating it as part of the gyre, the best approach to this eastern disturbance might be to describe it as mainly the result of a large-scale TC that developed from the zonally-oriented gyre convection (Figs. 10 and 16), outside of the primary gyre circulation and beyond the meridional band. It grew steadily, rapidly intensifying after the subtropical gyre center of circulation moved further west. While it develops and adopts the zonally-oriented convection of the gyre, the two circulations remain two separate maxima within the same large envelope of cyclonic circulation (Fig. 19). It becomes a matter of interpretation; they are part of the same cyclonic region, but they are local maxima separated by large distances. It is in the view of this work to regard them as separate, and although it briefly meets the gyre definition as explained in section 2, the eastern disturbance is too transient to meet the temporal requirements set forth by Chen et al. (2004).

A curious detail was noted in this study during the examination of Figs. 12 and 19. As the gyre developed and its cyclonic circulation expanded and intensified, an anticyclonic region to its south and southeast also intensified. This anticyclonic region maintained its size and intensity throughout the life of the gyre, and stayed within a few degrees of 140° W throughout the event. The possibility was considered that, drawing
from the work of Krouse et al. (2007), this might be a case of Rossby wave energy
dispersion from a cyclonic vortex. Krouse et al. (2007) showed using a shallow-water
model that for a vortex whose steering flow is westward with respect to the short
wavelength Rossby waves, eastward Rossby wave energy dispersion may occur, resulting
in a wave train east or southeast of the initial vortex. During the life of the gyre, there was
a portion of its life (1-3 August) where the gyre circulation moved on a generally
westward track (Fig. 20).

However, there are a number of complicating matters, some of which show that
the equatorward anticyclone cannot wholly be a result of Rossby wave dispersion. The
anticyclone was there before the gyre fully develops, and several days before it began
moving westward late in its life (Fig. 12). The eastern disturbance did not have an
anticyclone to its southeast (Fig. 19), and in fact, a weak area of positive vorticity
developed southeast of the disturbance (Figs. 19d and 19e). But since the movement of
the eastern disturbance was primarily northward with only a minor westward component,
it would have been unlikely to create a dispersion event as described by Krouse et al.
(2007). Looking into the literature to explain the appearance of the near-equator
anticyclone yielded no substantial results. Given the lack of knowledge regarding this
long-term anticyclonic region, it seems appropriate to describe the persistent equatorward
anticyclone as having experienced an enhancement due to dispersion from the westward
movement of the subtropical gyre. However, there are likely other factors that played a
crucial role in creating the anticyclone, and supporting its long duration in the tropics.

Section 3.4 Gyre Impacts
3.4.1 Gyre Impacts on TC Development

Previous work has noted that one of the most important impacts of subtropical gyres may be in causing significant track changes in TCs in the WNP, via binary interactions like those discussed in Ritchie and Holland (1993). Lander and Holland (1993) discuss this in some detail, stating that binary interactions result from a “capture” of vortices (a process that takes only a few hours) into an orbit where they influence other vortices in the region. The cyclones may then merge into each other, or environmental perturbations may release them to assume independent paths after some period of time. These binary interactions are demonstrated using observed TC track meanders in Holland and Lander (1993). Given the example, it is not difficult to imagine binary processes occurring with a TC and subtropical gyre, and Lander (1994) observed both vortex mergers and releases with the 1991 gyre. Lending further observational support to this behavior, Carr and Elsberry (1995) state that TCs interacting with subtropical gyres may suddenly adjust their tracks poleward. An average of 2-3 sudden poleward track alterations were recorded per year in JTWC data from 1977-1991, although many of these are not the result of subtropical gyres.

The 1989 subtropical gyre created a very difficult forecasting environment. In the case of the JTWC, vorticity maximum “C” (Figs, 8, 10, 15 and 16) was recognized as a tropical storm (TS Ken), then reported to have dissipated, only to have a new TC (TS Lola) form 12 hours later about 300 km west of where TS Ken was reported to have dissipated. In post-analysis, these were found to be the same storm, and the sources of error were given as a poorly-defined circulation and limitations on remote sensing (JTWC 1989). Furthermore, the JTWC had severe issues in determining the track of the
TC, with the 1200 UTC and 1800 UTC 30 July forecasts calling for it to make landfall on central and southern Japan (JTWC 1989, their Fig. 3-13-1). Given the obvious formation and tracking issues, it is worth examining the role the July 1989 subtropical gyre played on the formation and movement of TCs in the WNP.

Fig. 20 displays tracks of TCs that formed in close proximity to the gyre, with the gyre track used based on the smoothed position of the maximum circulation. The plot shows that both the gyre and Tropical Storm Ken-Lola (blue symbols; henceforth referred to as the KL TC) take similar tracks, and that the KL TC and gyre seem to coincide for a brief period of time on 2 August before the two separate, with the KLTC moving northwestward and the gyre taking a west to southwest track. In contrast, a TC that developed in the early stages of the gyre, TD 12W, appears unaffected by the gyre circulation to its southeast, taking a westerly track over the course of its short life. This is in stark contrast to the previous few days, when as vorticity maximum “B”, it completed a cyclonic orbit around the developing cyclonic center (Fig. 9). However, as noted in Fig. 17, the western and northwestern sides of the gyre were poorly developed early in the life of the mature subtropical gyre; it is plausible that the circulation was weak enough on its northwest side that it permitted TD 12W to move on a westward course unimpeded.

Fig. 21 shows the TC tracks once again, but in this figure, the gyre center is held constant, establishing a center-relative framework from which to examine the movement of the TCs. Most notable here is the movement of the KL TC; on 30 July, it was over 700 km from the gyre center, but as it moved north of the circulation, it began to spiral inward, being less than 400 km from the center by 0000 UTC 1 August. It would also appear that the TC was on the weaker northwest side of the gyre by this point, but the
gyre was developed enough by 1 August to wield an influence on the KL TC. Early on 2 August the centers of the TC and the gyre are only 100 km from each other, but they do not appear to fully merge, with the TC moving away from the center after 1200 UTC 2 August. Analysis not shown here indicates that Typhoon Mac (vorticity maximum “M” in Figs. 15 and 16) did not appear to experience significant influences from the subtropical gyre on its track. Likewise, the track of Typhoon Judy (vorticity maximum “J” in Figs. 8 and 10) was not significantly affected by the subtropical gyre, likely because it traversed the WNP while the gyre was still in its formative phase.

3.4.2 Gyre Impacts on the Large-scale Environment

While it is of substantial value to investigate the role of the subtropical gyre on TC development and movement, it is necessary to inquire about the role the gyre may play on the larger-scale environment of the subtropical WNP and beyond. One of the ways this can be examined is through use of velocity potential ($\chi$) fields. Velocity potential is a way of describing convergence and divergence in the upper-troposphere, and is useful for showing divergent flow patterns in the tropics and subtropics; in this manner, it can be used to show how the subtropical gyre impacts other large-scale features.

Fig. 22 illustrates the time-averaged velocity potential field and time-averaged convection and 200 hPa winds at various time periods before, during and after the development of the subtropical gyre. The first image, Fig. 22a, looks at 0000 UTC 20 July – 1200 UTC 25 July, the time period before the gyre started to develop. During this period, the convection is most prevalent over the Indian subcontinent and Bay of Bengal,
evidence of the active MJO phase in this region (Fig. 7). The regions of maximum
velocity potential (divergent regions) are over the Bay of Bengal and Southeast Asia, well
to the east of the gyre development region within the WNP. During the development
period of the gyre (1800 UTC 25 July – 0600 UTC 28 July, Fig. 22b), a clear brightness
temperature signal from the MJO-enhanced convection to the midlatitudes can be seen,
with strong upper-tropospheric winds aloft. The velocity potential maximum has shifted
to an area of intense convection over the WNP, this being the developing subtropical
gyre. In the last time period (1200 UTC 28 July – 1200 UTC 3 August, Fig. 22c), the
active convection over the Indian subcontinent has weakened, and the subtropical gyre
dominates the region with its strongly divergent wind field. Meanwhile the large-scale
outflow that might represent the MJO has propagated eastward into the vicinity of the
subtropical gyre. This is verified using the Hovmöller in Fig. 7. Effectively, one could
view the gyre as an expression of the active phase of the eastward-moving MJO signal.
IV. Discussion

4.1 Gyre Formation and Structure - A Timeline

The results as presented in Section 3 provide thorough evidence that the July 1989 subtropical gyre had origins that could be traced back to both tropical and extratropical events. The sequence of events is as follows:

1. An active MJO over the Indian subcontinent (Fig. 7) contributed, through diabatic heating, to the formation of a jet over central Asia and a jet exit region over northeastern Asia and the northwest coast of the Pacific Ocean. The jet can be seen in Fig. 5, while Fig. 6 notes the anomalous strength of the configuration.

2. The jet exit region allowed for upper-tropospheric midlatitude events to penetrate into the subtropics. By 24 July, one of these upper level troughs would extend deep into the subtropics, as it undergoes an equatorward wave-breaking event (Fig. 8).

3. Meanwhile, smaller-scale convection developed within the subtropics and moved eastward, into the area of the upper-level trough. It is hypothesized that with greater instability in the vicinity of the trough, the convection was able to grow in size and magnitude as it interacted with the upper-level low, creating a low-level vorticity maximum that moved cyclonically around the upper low during and after the completion of wave-breaking event. This is shown in Fig. 9.

4. The growing convection intensified cyclonic vorticity maxima through diabatic heating (“B” in Figs. 8 and 10). The diabatic heating also reduced the surface pressure, increasing the pressure gradient and the surface winds by extension. This allowed the developing convective mass to tap into greater amounts of the
vast quantity of heat energy stored in the upper layers of the WNP (Figs. 3 and 10). More vorticity maxima developed ("C" and "D" in Figs. 8 and 10), and moved around the upper-level low, with convection filling in a large zonal band before extending poleward east of the low. However, at this time, the convection did not follow the vorticity maxima poleward (Fig. 9).

5. As the gyre first met the definition at 1200 UTC 28 July (Fig. 13), vorticity maximum “B” completed 3/4ths of a cyclonic orbit. Enough convection built within “B” that it was declared a TD. The TD continued due west, as the underdeveloped western flank of the gyre was too weak to affect its track (Figs. 20 and 21). The initial structure of the gyre could be described as cyclonic but asymmetric, with strong winds to its north, east and south, but not to the west (Fig. 17).

6. The gyre underwent a structural evolution with a second equatorward wave-breaking event caused by the same trough as before. The trough retrograded and moved westward as a result of the upper-level flow induced by a diabatic ridge (Fig. 9). The convective tail of Typhoon Judy, which was predicted by the off-equatorial heating models of Heckley and Gill (1984), combined with the persistent zonally-oriented convection to expand the gyre’s convective envelope eastward and poleward (Figs. 8 and 10). Meanwhile, the cyclonic core of the gyre deepens and strengthens (Fig. 18).

7. Within the mature gyre, more vorticity maxima developed, but these were short-lived. A second TC developed from vorticity maximum “C” as it rotated poleward and then westward before spiraling inward to the center of the gyre circulation.
This suggests that the northwestern portion of the gyre became better developed, and this is verified in Fig. 17. As the TC moved toward the center, the eastern meridionally-oriented convection disintegrated, and more of the zonal convection was caught up in the developing TC to the east (‘M’ in Figs. 15 and 16).

8. After a period of about 12 hours where the TC and gyre center were in close proximity of each other (Fig. 21), the TC broke away and moved westward into the Asian continent, while the gyre, lacking nearby strong vorticity maxima, no longer met the definition after 0600 UTC 3 August (Fig. 14).

Through these results, it is shown that the subtropical gyre was a product of multiple events that varied on location and spatial scale, and that no one component can necessarily be taken away and still result in the formation of the gyre. These range from smaller-scale areas of convection in the WNP, to multiple penetrations of upper-level troughs from the midlatitudes, to an active MJO influencing the midlatitude flow such that the configuration of jet streaks and exit regions made it favorable for a wave-breaking event over the warm waters of the WNP.

4.2 Comparisons to the July 1988 Subtropical Gyre

With the wealth of information presented in this work, it is worth taking a second look at the July 1988 subtropical gyre analyzed by MV2012, to give a sense of characteristics that are common to gyres, and features that are somewhat more unique to individual cases. First, a review of what is common to both cases:

1. Both cases occurred during mid-summer during La Niña.
2. Both cases formed from midlatitude forcing in the form of equatorward wave breaking events. In both cases, an active MJO contributed diabatic heating to transform the jet stream into a configuration favorable for wave breaking, and both cases show a realignment of upper-level outflow that suggests eastward propagation of the MJO signal into the gyre regions.

3. Both cases exhibit deep cyclonic structure, with the 1988 case encompassing the surface to 200 hPa vertical layer, and the 1989 case extending to a similar height during its mature stage.

However, while there are substantial similarities between the two events, there are also some important differences:

1. The role of the midlatitude forcing in the 1989 case appears to be less direct. In the 1988 case described in MV2012, multiple midlatitude lower-tropospheric lows moved equatorward during the formation of the subtropical gyre, and these provided the cyclonic vorticity and convection that aggregated into a large gyre. In that case, only one low-level vorticity maxima had its origins in the subtropics (their vorticity maximum “E”). In the 1989 case, an upper-tropospheric low is deposited into the subtropics, where vorticity maxima that form in situ interact with the upper-level low, eventually establishing enough strong cyclonic maxima to produce a gyre.

2. In the 1988 case, the gyre stayed relatively stationary, with limited convective and vorticity development well to its east. In the 1989 case, a strong cyclonic circulation arose east of the gyre, concurrent with the formation of a TC. These
events could be tied into an eastward propagation of the active MJO signal, and are a feature that is not apparent in the 1988 case of MV2012.

3. In MV2012, Q-vector divergence is used to show forcing for descent and ascent correlated closely with cloudless and convective regions respectively. Using a similar calculation (same smoothing, same temporal averaging) in analysis of the 1989 subtropical gyre yielded inconsistent results, with some daily time periods showing significant forcing for descent in convectively active regions. This suggests that while Q-vector forcing may be helpful in gyre formation and growth, it does not appear to be essential, or its application may need to be refined further.

It is important to note that this work and MV2012 use different centering methods, as MV2012 uses a centering method based on pressure minimum versus the point of maximum 900-1200 km averaged circulation used here. However, when the 900-1200km averaged circulation is applied to MV2012, the centers are nearly identical.

4.3 A Bigger Picture of Subtropical Gyres

One of the biggest questions that need to be addressed in future work is the rate of occurrence of subtropical gyre events. Although subtropical gyres have usually been analyzed in the form of a case study of a single event, there is some circumstantial evidence that gyres make regular appearances in the WNP. While conducting an analysis of WNP TC wind profiles using azimuthally averaged wind radii, Cocks and Gray (2002) noted that an unusual subset of TCs was observed in their data, with very large wind radii, but with generally weak wind maxima, adopting the term “gyre systems” in describing this special TC class. Of the 35 TCs examined between 1980 and 1987, five met their “gyre system”
requirements of giving a 15 m/s wind radius greater than 300 km, and a central pressure of 990 hPa or less. These storms remained consistently large throughout their measured lifespans, with only weakly varying minimum central pressures in the composite life cycle. Four of the five gyre systems occurred in August or early September, between 20° N and 30° N and 120° and 135° E (the fifth developed in October near (15° N, 115° E)). The authors stated that, following the example of TY Gladys of the August 1991 subtropical gyre reviewed in Lander (1994) believed that this subset of TCs were the result of a TC merging with the center of a synoptic-scale cyclone. However, it is quite possible, given the strict pressure and wind radii-based definition provided in Cocks and Gray (2002), that for much of the lifespan of the “gyre TC”, they might have been examining the gyres themselves, rather than a TC that developed in the peripheral convection and then merged with the gyre center.

Camargo et al. (2007) used a complex probabilistic clustering method based on a regression mixture model to describe TC formation and propagation in the Western Pacific. When applied to the Joint Typhoon Warning Center (JTWC) best track data set from 1950-2002, seven distinct clusters of storm varieties were identified. The “Cluster A” set of TCs of Camargo et al. (2007) indicates environmental anomalies whose structure is remarkably similar to that of subtropical gyres. Fig. 4 of Camargo et al. (2007) displayed anomalous 850 hPa winds and vorticity of “Cluster A”. These showed large-scale cyclonic wind and positive vorticity anomalies centered near 20°N, 130°E, with the mean area of TC genesis occurring southeast of the cyclonic anomaly center, near 18°N, 135°E. Later figures showed the presence of anomalously low OLR and anomalously low sea level pressures in the same vicinity. Fig. 8 of Camargo et al. (2007), a composite of daily total wind shear from 850 hPa
upwards to 200 hPa, indicated that the midlatitude jet from 120° E to 160° E during “Cluster A” occurrences is the weakest of any of the clusters, which would indicate a possible jet exit to the west and dynamic favorability for events such as the equatorward wave breaking observed prior to the formation of the July 1988 subtropical gyre. The authors note that “Cluster A” occurs more frequently in La Niña years, and when the MJO is convectively active over the Maritime Continent or the eastward portion of the WNP (MJO Phases 5 and 6 respectively, according to Wheeler and Kiladis (2004)). Given these previous works, it seems likely that subtropical gyres are a regular occurrence, but a climatology of these events, and resolving what proportion of TC cyclogenesis cases they are involved in within the WNP, is something that needs to be undertaken in a future study.

Another question that needs to be answered is the role of the MJO within the framework of the subtropical gyre. In both the July 1988 case examined by MV2012 and the July 1989 case viewed here, the MJO played an important if indirect role in producing an environment favorable for gyre formation. In relation to the work of Camargo et al. (2007), it has been noted that ENSO phases modulate the activity and location of the propagating MJO (Hendon et al. 2008). Since this would affect how and where it influences the extratropics, and by extension where regions of favorable wave-breaking are created, this may be part of the explanation to why the 1991 case, which occurred during an ENSO-positive (El Niño), was located 20° degrees further east. Perhaps more importantly, as the gyre seems to benefit from the eastward propagation of the active MJO signal by the enhancement of its equatorward zonally-oriented convection (Fig. 22), it could be suggested that the subtropical gyre is in fact a direct product of an active MJO. Under what conditions an active MJO may lead to subtropical gyre formation is something that also needs to be explored in further work.
REFERENCES


Figure 1. GMS-3 visible (0.6 µm) satellite imagery once daily at 0000 UTC (a) 28 July (b) 29 July (c) 30 July (d) 31 July 1989. The red box indicates the approximate center of the gyre, defined as the location of the maximum 900-1200 km azimuthally-averaged circulation.
Figure 2. 850 hPa zonal wind (upper panels, in m s\(^{-1}\)) and IR brightness temperature (lower panels, in degrees Kelvin) Longitude-Time (Hovmöller) diagrams for 1 Jul – 15 Aug 1989. The left panels are averaged over 6°N-16°N, the right panels over 16°N-26°N. Warm colors in the zonal winds indicate westerlies, and cool colors indicate easterlies. Shading begins at ± 3 m s\(^{-1}\) with increments of 3 m s\(^{-1}\). The black asterisks represent the position of the gyre when it first met definition criteria at 1200 UTC 28 July 1989.
Figure 3. Averaged sea-surface temperatures (SSTs, in degrees Kelvin) for 6 July – 26 July 1989, the three weeks immediately prior to gyre formation. Red shading indicates values of 302 – 304 K (29-31°C). The “L” indicates the approximate center of the gyre when it first meets the gyre definition. The dashed contours indicate the 303 K (30°C) isotherm.
Figure 4. 200 hPa zonal wind (left, in m s\(^{-1}\)) Hovmöller diagram for 1 June – 15 August 1989, averaged 30°N-40°N. Warm colors indicate westerlies, and cool colors indicate easterlies. Shading begins at ± 6 m s\(^{-1}\) with increments of 6 m s\(^{-1}\).
Figure 5. Time-averaged 200 hPa wind velocity plot for 15 July – 25 July 1989. Shaded colors indicate wind speeds at 200 hPa in increments of 10 m s$^{-1}$. Vector arrows indicate direction and magnitude of 200 hPa winds. Black contours indicate 200 hPa height in increments of 60 meters.
Figure 6. 200 hPa zonal wind (shaded, in m s$^{-1}$) and 200 hPa wind vector anomalies (arrows) averaged for 15 Jul – 25 Jul 1989. Shading begins at ± 2.5 m s$^{-1}$ with increments of 2.5 m s$^{-1}$. Image based off NCEP/NCAR Reanalysis and obtained from ESRL. Source: http://www.esrl.noaa.gov/psd/data/composites/day/
Figure 7. Longitude-time diagram of OLR (shaded, with cool colors representing active convection) and MJO-filtered OLR (red contours; solid represent active MJO, dashed suppressed), each averaged 7.5 – 17.5°N. OLR is unfiltered except for removal of the seasonal cycle. The black asterisk represents the position of the gyre when it first met definition criteria at 1200 UTC 28 July 1989. On this Hovmöller diagram only, time increases upward.
Figure 8. Ertel potential vorticity on the 350K isentropic surface (PVU, shaded), 850 hPa wind (vectors), and 850 hPa vorticity (contours) once daily at 1200 UTC (a) 24 July; (b) 25 July; (c) 26 July; (d) 27 July; (e) 28 July; and (f) 29 July 1989. 850 hPa vorticity is plotted only for values above $1 \times 10^{-5}$ s$^{-1}$ in increments of $2 \times 10^{-5}$ s$^{-1}$. The upper case letters follow individual vorticity maxima at 850 hPa. The green upper case “L” represents the center of the gyre circulation.
Figure 9. Ertel potential vorticity on the 350K isentropic surface (PVU, shaded), 350 K wind (vectors), and 850 hPa vorticity (contours) once daily at 1200 UTC (a) 27 July; (b) 28 July; (c) 29 July 1989. As before, 850 hPa vorticity is plotted only for values above 1 x 10^{-5} s^{-1} in increments of 2 x 10^{-5} s^{-1}. The upper case letters follow individual vorticity maxima at 850 hPa. The green upper case “L” represents the center of the gyre circulation.
Figure 10. CLAUS brightness temperature (degrees Kelvin, shaded), 850 hPa wind (vectors), and 850 hPa vorticity (contours) once daily at 1200 UTC (a) 24 July; (b) 25 July; (c) 26 July; (d) 27 July; (e) 28 July; and (f) 29 July 1989. 850 hPa vorticity is plotted only for values above $1 \times 10^{-5}$ s$^{-1}$ in increments of $2 \times 10^{-5}$ s$^{-1}$. The magenta upper case letters follow individual vorticity maxima at 850 hPa. The green upper case “L” represents the center of the gyre circulation. The green hurricane symbols represent the center locations of TCs as determined by JMA data.
Figure 11. CLAUS brightness temperature (degrees Kelvin, shaded), surface wind (vectors), and oceanic surface latent heat flux (contours) once daily at 1200 UTC (a) 24 July; (b) 25 July; (c) 26 July; (d) 27 July; (e) 28 July; and (f) 29 July 1989. Heat flux values are plotted only for values above 75 W m$^{-2}$ in increments of 50 W m$^{-2}$. Hatching is applied to values above 175 W/m$^2$, and cross-hatching above 275 W m$^{-2}$. The green upper case “L” represents the center of the gyre circulation.
Figure 12. 850 hPa 900-1200 km averaged circulation plotted on a gridded field and contoured once daily at 1200 UTC for a) 25 July; b) 26 July; c) 27 July; d) 28 July; and e) 29 July 1989. Red shading indicates cyclonic circulation greater than $1 \times 10^{-7}$ m$^2$ s$^{-1}$. Blue shading indicates anticyclonic circulation less than $-1 \times 10^{-7}$ m$^2$ s$^{-1}$. 
Figure 13. Daily 1200 UTC 850 hPa azimuthally averaged tangential velocity vs. radius plots (a, in m s\(^{-1}\)) and azimuthally averaged circulation vs. radius plots (b, in units of 10\(^{-7}\) m\(^2\) s\(^{-1}\)). Plotted are values for 27 July (blue line), 28 July (red line), 29 July (pink line) and 30 July 1989 (maroon line). The green line indicates where plotted values equal zero.
Figure 14. Daily 1200 UTC 850 hPa azimuthally averaged tangential velocity vs. radius plots (a, in m s\(^{-1}\)) and azimuthally averaged circulation vs. radius plots (b, in units of \(10^{-7}\) m\(^2\) s\(^{-1}\)). Plotted are values for 31 July (blue line), 1 August (red line), 2 August (pink line) and 3 August 1989 (maroon line). The green line indicates where plotted values equal zero.
Figure 15. Ertel potential vorticity on the 350K isentropic surface (PVU, shaded), 850 hPa wind (vectors), and 850 hPa vorticity (contours) once daily at 1200 UTC (a) 30 July; (b) 31 July; (c) 1 August; (d) 2 August 1989. 850 hPa vorticity is plotted only for values above $1 \times 10^{-5}$ s$^{-1}$ in increments of $2 \times 10^{-5}$ s$^{-1}$. The upper case letters follow individual vorticity maxima at 850 hPa. The green upper case “L” represents the center of the gyre circulation.
Figure 16. CLAUS brightness temperature (degrees Kelvin, shaded), 850 hPa wind (vectors), and 850 hPa vorticity (contours) once daily at 1200 UTC (a) 30 July; (b) 31 July; (c) 1 August; (d) 2 August 1989. 850 hPa vorticity is plotted only for values above $1 \times 10^{-5}$ s$^{-1}$ in increments of $2 \times 10^{-5}$ s$^{-1}$. The magenta upper case letters follow individual vorticity maxima at 850 hPa. The green upper case “L” represents the center of the gyre circulation. The green hurricane symbols represent the center locations of TCs as determined by JMA data.
Figure 17. Vertical cross-sections of zonal wind velocities at 1200 UTC for (a) 29 July (b) 31 July and (c) 2 August 1989, in increments of 5 m s$^{-1}$, from south to north on the x-axis. Meridional wind velocities at 1200 UTC are shown for the same dates, in figures (d, e, f) respectively, with the same increments of 5 m s$^{-1}$, and from west to east on the x-axis.
Figure 18. Vertical cross-sections of relative vorticity at 1200 UTC for (a) 29 July (b) 31 July and (c) 2 August 1989, in increments of $2 \times 10^{-5}$ s$^{-1}$, from south to north on the x-axis. Shaded areas represent regions of positive (cyclonic) vorticity.
Figure 19. 850 hPa 900-1200 km averaged circulation plotted on a gridded field and contoured once daily at 1200 UTC for a) 30 July; b) 31 July; c) 1 August; d) 2 August; and e) 3 August 1989. Red shading indicates cyclonic circulation greater than $1 \times 10^{-7}$ m$^2$ s$^{-1}$. Blue shading indicates anticyclonic circulation less than $-1 \times 10^{-7}$ m$^2$ s$^{-1}$. 
Figure 20. Latitude-longitude plots of gyre and storm locations, in six-hourly intervals for 1200 UTC 28 July – 1200 UTC 3 August 1989. Orange TC symbols indicate the gyre center, green TC symbols indicate TD 12W (advisories issued from 0600 UTC 29 July to 0600 UTC 30 July), and blue TC symbols indicate the location of TS Ken-Lola (first advisories issued at 0600 UTC 29 July 1989).
Figure 21. Movement of the TC with respect to the gyre circulation center, presented on a cylindrical grid. The innermost circle, shaded in gray, represents within 100 km of center. The outer concentric lines begin at 200 km and are in increments of 200 km. The green dots represent TD12W, based on JTWC track. The plotted locations are for winds of 30 kt. or greater. The blue dots are for the KL storm, based on JMA data, running from 1200 UTC 28 Jul – 0600 UTC 3 Aug 1989.
Figure 22. Velocity potential (contours; increment $3 \times 10^6 \text{ m}^2 \text{s}^{-1}$) and divergent part of the wind (vectors), both at 200 hPa, and infrared brightness temperature (shaded, in degrees Kelvin), averaged (a) 0000 UTC 20 July – 1200 UTC 25 July (b) 1800 UTC 25 July – 0600 UTC 28 July (c) 1200 UTC 28 July – 1200 UTC 3 August 1989.