13D.8 THE FORMATION AND EVOLUTION OF THE 1989 WESTERN NORTH PACIFIC SUBTROPICAL GYRE

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1. INTRODUCTION

In July 1989, during a La Niña event, a broad area of deep convection to the east of The Philippines evolved into a large cyclonic gyre that persisted for several days. The gyre exhibited an asymmetric convective structure, with activity concentrated on the southern and eastern sides and a relatively clear center. The gyre also maintained cyclonic winds at 850 hPa over a radius greater than 2000 km. In the period prior to the gyre's development, an active MJO was in place over the Indian Ocean and Indian subcontinent, followed by anticyclonic wave breaking associated with an upper tropospheric jet exit region over northeast Asia. The wave breaking left an area of upper tropospheric cyclonic vorticity in the subtropics, and also initiated the development of convection, which generated cyclonic vorticity in the lower troposphere. The interaction of the upper and lower vorticity centers created conditions favorable for increased convection and a growth and intensification of the low-level vorticity center into a large gyre. As the gyre matured, azimuthally-averaged tangential winds and circulation increased. Two tropical cyclones developed within the asymmetric convection of the gyre. The active MJO and negative ENSO phases, as well as the July 1989 gyre's structure, bear strong similarity to a previously studied gyre in July 1988 by Molinari and Vollaro (2012). The evolution of the gyre, as well as details regarding its initial formation, will be discussed.

2. DEFINITION OF A SUBTROPICAL GYRE

In this work, a disturbance is considered to be a subtropical (monsoon) gyre when the azimuthally-averaged tangential velocity at 850 hPa remains positive outwards from the center to a radius of 2000 km, and that the tangential winds maintain an azimuthally-averaged velocity of at least 8 m s^{-1} at some radius within 2000 km. This differs from the definition provided by Lander (1994) and Chen et al. (2004) in that it requires a cyclonic feature to have a larger radius (2000 km vs. 1250 km), and that it includes a minimum tangential velocity. Although a temporal requirement is not given with the working definition here, when applied to the 1989 event, it is found that the subtropical gyre meets the definition parameters for six days, which meets the criteria of five days or longer set forth by Chen et al. (2004), but not the two to three week life span suggested by Lander (1994).

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3. THE FORMATION OF THE SUBTROPICAL GYRE

3.1 Large-Scale Background and Environment

Several events in the tropics and midlatitudes contributed to the creation of an environment favorable for the formation of the 1989 subtropical gyre. Prior to the development of the gyre, an active MJO phase was present from 70° E – 100° E, in the vicinity of the Indian subcontinent and the Indian Ocean (Fig. 1a). A strong MJO-midlatitude teleconnection existed before and during the formation of the gyre, as evidenced by the convection and 200 hPa winds in Fig. 1b.

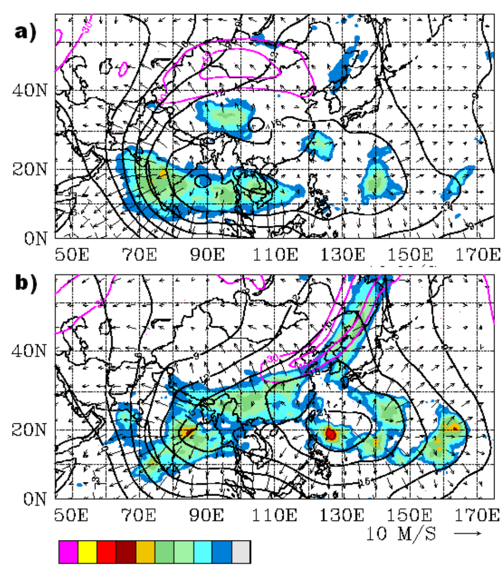

Fig. 1. Velocity potential (black contours; increment 3 x 10^6 m^2 s^{-1}), wind speed (pink contours, increment 15 m s^{-1} starting at 30 m s^{-1}) and divergent part of the wind (vectors), all at 200 hPa, and infrared brightness temperature (shaded, in degrees Kelvin), all averaged from a) 0000 UTC 20 July – 1200 UTC 25 July 1989 and b) 1800 UTC 25 July – 0000 UTC 28 July 1989.

In the midlatitudes prior to gyre formation, a jet exit region persisted over northeastern Asia and the northwestern Pacific Ocean (Fig. 2). When compared to the climatological mean for this time of the year, it is shown that westerlies are anomalously strong over central Asia and anomalously weak over Japan and the northern Pacific Ocean (Fig. 3). However, this configuration, especially with regards to the active MJO, may not be uncommon. The same setup occurred with the gyre examined by Molinari and Vollaro (2012). Furthermore, Ding et al. (2011) found a climatological correlation between positive summer rainfall anomalies over the Indian subcontinent, and the formation of a midlatitude jet developing over far northeastern Asia, creating a jet exit region over the northwestern Pacific Ocean.

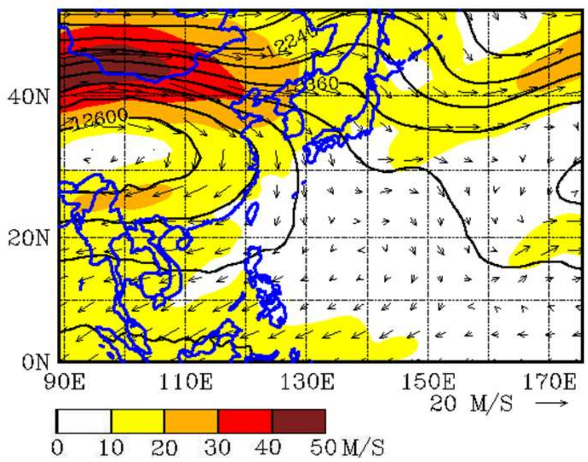

Fig. 2. Time-averaged 200 hPa winds for 15 July – 25 July 1989. Shaded colors indicate wind speeds at 200 hPa in increments of 10 m s^{-1}. Vectors indicate direction 200 hPa winds. Black contours indicate 200 hPa heights, in increments of 60 meters.

More importantly, the jet exit region provides an upper-level atmospheric circulation suitable for an equatorward (anticyclonic) wave-breaking event (Moore *et al*. 2010), which plays a major role in the formation of the subtropical gyre. In summary, diabatic heating from an active MJO phase influenced midlatitude flow, which developed an upper-level jet over central Asia and a jet exit region that supplied a configuration favorable for upper-level cyclones to penetrate deep into the subtropics.

3.2 The Formation of the Subtropical Gyre

3.2.1 Formation from a Vorticity Perspective

At 24 July 1989 1200 UTC, an upper-level trough over Japan extended well into the subtropics to about 20° N (Fig. 4a). This is the initial disturbance that

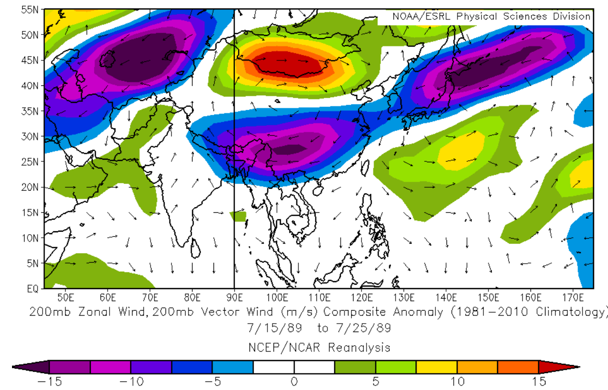

Fig. 3. 200 hPa zonal wind anomalies (shaded, in m s^{-1}) and 200 hPa wind vector anomalies (arrows) averaged for 15 Jul – 25 Jul 1989. Shading begins at ± 2.5 m s^{-1} with increments of 2.5 m s^{-1}. Image based off NCEP/NCAR Reanalysis and obtained from ESRL. Source : http://www.esrl.noaa.gov/psd/data/composites/day/

engages in the wave-breaking event. Although the trough is directly responsible for the creation of low-level vorticity maximum "A", "A" does not play a role in the development of the gyre and is quickly absorbed by the existing tropical cyclone (TC) in the region (TY Judy, referred to as "J"). However, over the following few days, low-level vorticity maximum "B", which developed from tropical convection upstream of the trough around (Fig. 4b) rotates cyclonically around the breaking wave (Fig. 4c), using the more destabilized environment to develop as it rotates. Vorticity maximum "C" develops in the same region that "B" did (Fig. 4d), but does not move in any significant cyclonic rotation around the cutoff upper-level PV anomaly. By 28 July 1200 UTC, as vorticity maximum "D" arises between the cyclonic flow of "B" and "C", our gyre definition criteria are fulfilled by the disturbance, with the center of circulation located at "L" (Fig. 4e). The following day (29 Jul 1200 UTC) represents the mature gyre, with "B" having made a nearly complete cyclonic revolution around the center of circulation, which is defined primarily by the cyclonic vorticity associated with "B", "D", and the newly formed "E" (Fig. 4f). From this sequence, we are made aware of the role of the wave-breaking; low-level vorticity maxima take part in a binary interaction with the cutoff PV anomaly in the subtropics, and the development of multiple maxima around a common center produces a large low-level cyclonic circulation that can be defined as a subtropical gyre. The prominent role of the midlatitudes bears similarity to the 1988 case from Molinari and Vollaro (2012), with the key difference that the low-level vorticity maxima that developed ahead of the upper-level trough did not contribute directly to the development of this gyre as it did in the 1988 case.

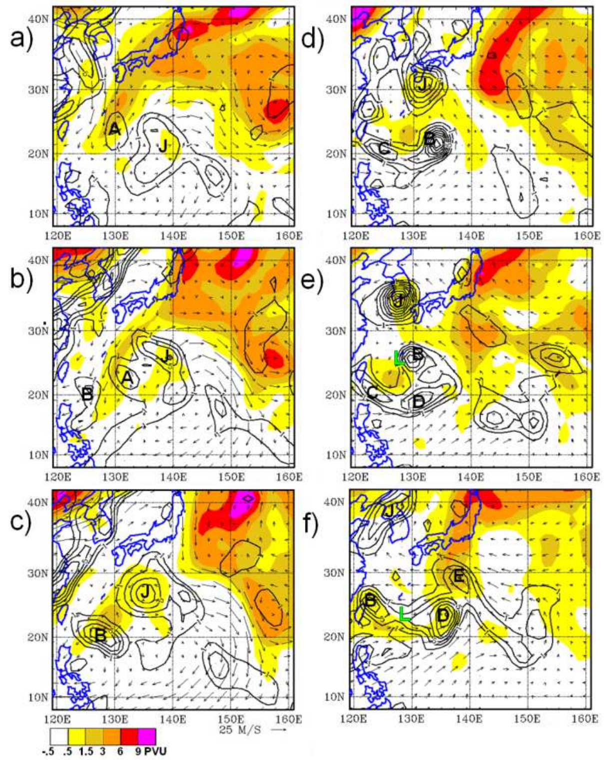

Fig. 4. Ertel potential vorticity on the 350K isentropic surface (PVU; shaded), 850 hPa wind (vectors), and 850 hPa vorticity (contours) at 1200 UTC for a) 24 July b) 25 July c) 26 July d) 27 July e) 28 July f) 29 July 1989. 850 hPa vorticity is plotted only for values above $1 * 10^{-5}\ s^{-1}$ in increments of $2 * 10^{-5}\ s^{-1}$. The upper case letters follow individual vorticity maxima at 850 hPa. The green "L" indicates the approximate center of the gyre circulation.

3.2.2 Formation from a Convection Perspective

Analyzing the same set of imagery from a convective standpoint displays another facet of the development of the subtropical gyre. At 24 July 1989 1200 UTC (Fig. 5a), we can see sporadic convection in the region outside of the "J" TC. The following day, we can see the convection associated with a nascent vorticity maximum "B" (Fig. 5b), and this continues to intensify on 26 July (Fig. 5c). The convection is contributing to the growth of the cyclonic vorticity via diabatic heating. As convection begins to fill in a roughly linear band, "B" begins to move northward around the upper-level PV anomaly, and has little convection, while "C" is located within deep convection (Fig. 6a). More convection fills in around 20°N over a span over 40° longitude, while poleward convection fills in near 145° E (Fig. 6b), perhaps residual from the TC. Meanwhile , "B" continues to generate little convection. The mature gyre (Fig. 6c) has clear equatorward and eastward flanks of convection, while "B" has developed some convection at this point. "B" was monitored at this time as a tropical depression, and "D" is declared a TC (TS Ken) by this time.

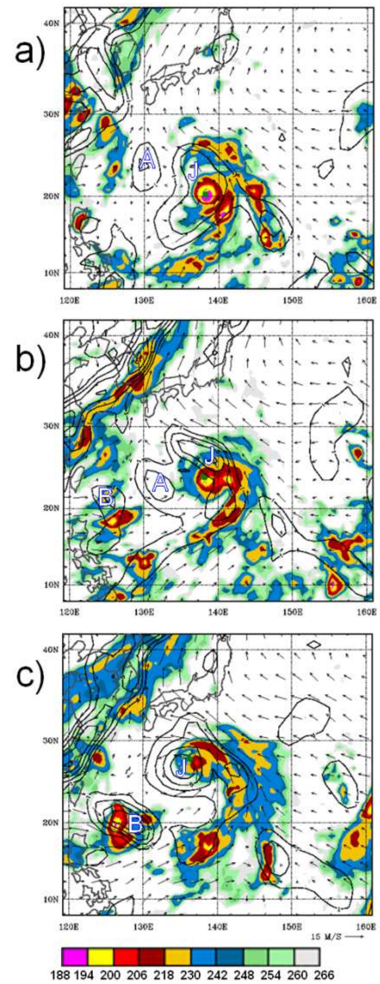

Fig. 5. 850 hPa vorticity (black contours), 850 hPa winds (vector arrows) and CLAUS brightness temperature fields (shaded, in degrees Kelvin) at 1200 UTC for a) 24 July b) 25 July c) 26 July 1989. Contours begin at $1 * 10^{-5}\ s^{-1}$, with increments of $2 * 10^{-5}\ s^{-1}$. The upper case letters follow individual vorticity maxima at 850 hPa. TCs (based off of JMA data) shown by green TC symbols.

3.2.3 The Importance of Heat Fluxes

One thing that becomes quite apparent upon further analysis is the role of oceanic latent heat flux on the development of the subtropical gyre. As shown in Fig. 7, gyre convection is sustained by large amounts of energy transfer into the atmosphere, which drive convective development. In turn, through diabatic heating producing lower surface pressures and enhancing surface winds, heat fluxes may be intensified by convection. This relationship is a major contributor to

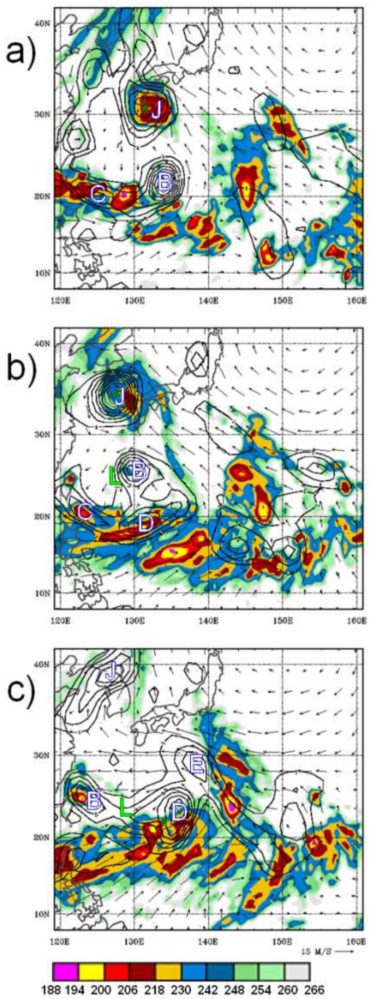

Fig. 6. 850 hPa vorticity (black contours), 850 hPa winds (vector arrows) and CLAUS brightness temperature fields (shaded, in degrees Kelvin) at 1200 UTC for a) 27 July b) 28 July c) 29 July 1989. Contours begin at 1 * 10^{-5} s^{-1}, with increments of 2 * 10^{-5} s^{-1}. The upper case letters follow individual vorticity maxima at 850 hPa. TCs (based off of JMA data) shown by green TC symbols.

gyre development, since the large area of deep convection requires a substantial amount of energy transfer supplied from the top layer of the tropical ocean and its vast heat storage. This may also help explain why gyres are generally observed in July or August, when temperatures in the boreal ocean surface layer exceed 30° C in the subtropics.

This talk will focus on the dynamics involved with the formation of the subtropical gyre, and seeks to highlight the interaction between the tropics and the extratropics to produce this large-scale cyclonic disturbance. The strong similarities between the findings of this work and the research previously done by Molinari and Vollaro (2012) in their 1988 case seem to suggest a specific set of requirements for gyre formation, and the better understanding we have of the processes that lead to their formation, the better we will be able to identify future gyres as they develop.

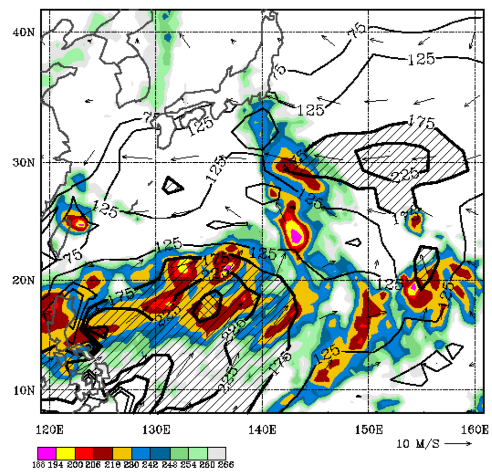

Fig. 7. CLAUS brightness temperature (shaded), surface winds (vectors) oceanic surface latent heat flux (contours) for 29 July 1989 0000 UTC. Heat flux values are plotted only for values above 75 W/m^2 in increments of 50 W/m^2 . Hatching is applied to values above 175 W/m^2, and double hatching above 275 W/m^2.

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