Role of monsoon gyre in the interannual variation of tropical cyclone formation over the western North Pacific

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Abstract
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Keywords
atmospheric temperature, correlation methods, frequencies, storms, Interannual variation, tropical cyclones, weather forecasting, air-sea interaction, annual variation, gyre, monsoon, sea surface temperature, tropical cyclone, Pacific Ocean

Disciplines
Atmospheric Sciences | Geology

Comments
NOTES AND CORRESPONDENCE

Role of the Monsoon Gyre in the Interannual Variation of Tropical Cyclone Formation over the Western North Pacific

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ABSTRACT

The south-southeast periphery of a monsoon gyre in the western North Pacific (WNP) is a favorable region for tropical cyclone/tropical depression (TC/TD) genesis. The TC genesis frequency is interannually modulated by the WNP monsoon circulation in response to a change in tropical Pacific sea surface temperature (SST). These findings from previous studies lead to the hypothesis that the effect of tropical Pacific SST changes on the WNP TC/TD genesis frequency is accomplished through a modulation of the monsoon gyre activity by WNP monsoon circulation variations. The 6-h TC/TD track records and NCEP–NCAR reanalysis data for the period of 1979–2002 were analyzed to test this hypothesis. Results show that roughly 70% of WNP TC/TD genuses are linked to monsoon gyres. The interannual variation of these genuses is highly correlated (with a correlation coefficient of 0.89) with that of monsoon gyre activity, which is out-of-phase with the interannual variation of SST over the NOAA Niño-3 region.

1. Introduction

The interannual variation of tropical cyclone (TC) genesis occurrence over the western North Pacific (WNP) has been suggested to be caused by two mechanisms. First, the east–west circulation over the tropical Pacific may be modulated by the interannual variation of sea surface temperatures (SSTs) following the El Niño–Southern Oscillation (ENSO) cycle. The upward branch of this circulation over the western tropical Pacific is weakened (intensiﬁed) and TC genesis in the WNP is consequently suppressed (enhanced) when central-eastern tropical Paciﬁc SSTs become warmer (cooler) (Dong 1988; Wu and Lau 1992; Lander 1994a, and others). Therefore, an interannual east–west ﬂuctuation in TC genesis may be exhibited over the western tropical Paciﬁc. Second, the East Asian low-level circulation response to central tropical Paciﬁc SST anomalies (associated with the ENSO cycle) is through an anomalous meridional teleconnection wave train (formed by east–west-elongated cells, which will be shown later) emanating from the tropical western Paciﬁc (Nitta 1987; Chen and Weng 1998; Chen et al. 1998; Lau et al. 2000, and others). This anomalous wave train consists of a tropical negative (positive) cell and a subtropical positive (negative) cell during the positive (negative) phases of summer ΔSST (Niño-3) anomalies (≥|0.5°C|). Consequently, the TC genesis frequency over the western tropical Paciﬁc undergoes an interannual north–south variation following the anomalous meridional wave train (Chen et al. 1998). By these two mechanisms, tropical Paciﬁc SST anomalies impact TC activity by changing the large-scale circulation.

Lander (1994b) observed that a monsoon gyre with a horizontal scale of 2500 km may be formed over the western tropical Pacific along the convergence zone between the monsoon westerlies and the trade easterlies. Coupled with this low-level monsoon gyre is a weak upper-level ridge/anticyclone. The low-level confluent flow along the southeast rim of this monsoon gyre and the corresponding upper-level difﬂuent ﬂow constitute an environment conducive to enhanced convective activity and TC genesis. Lander’s (1994b) ﬁndings of the relationship between the monsoon gyre and small-scale tropical vortices, such as tropical depressions (TDs), were echoed by Holland’s (1995) argument of scale interaction in the western Paciﬁc monsoon. The TC–monsoon gyre interactions sometimes become the cause of sudden poleward TC track changes (Carr and Elsberry...
1995). At any rate, the monsoon gyre identified by Lander (1994b) functions as a facilitator of TC/TD genesis in the WNP. Examining the annual tropical cyclone reports of the Joint Typhoon Warning Center (JTWC) at Guam and geostationary satellite imagery, Lander (1994a) also pointed out that the monsoon gyre—by his definition—appears at a rate of approximately once every two years (from late July through early September). In view of the role played by the monsoon gyre in TC/TD genesis, it is likely that the tropical Pacific SST anomalies impact TC/TD genesis over the WNP through monsoon gyre activity. Because this impact has not been explored yet, the role played by the monsoon gyre in the interannual variation of WNP TC/TD genesis was examined in the present study using several datasets for the period 1979–2002.

2. Data and analysis

Three different types of data were analyzed in the present study: 6-h TC/TD track records, the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data (Kalnay et al. 1996), and daily precipitation data generated by three projects. The TC/TD track records consist of two datasets: 1) 6-h TC tracks collected by the Regional Specialized Meteorological Center with the Forecast Division of the Japan Meteorological Agency (JMA), and 2) 6-h TC/TD track records archived by the Joint Typhoon Warning Center. Track records of both TC and TD from both sources were blended into our analysis based on two motivations. First, the JMA archives only maintain the named TC tracks that were analyzed by Chen et al. (1998). In order to contrast the results of this study with those of Chen et al., we again analyzed the JMA TC tracks. Second, since TD tracks are not available in the JMA archives, the JTWC TD track records were used instead. Daily precipitation data were derived from the Microwave Sounding Unit (MSU; Spencer 1993), Goddard precipitation estimations (GPI; Susskind et al. 1997), and the Global Precipitation Climatology Project (GPCP; Huffman et al. 1997). Daily precipitation is used to identify monsoon gyres. The three daily precipitation datasets (MSU, GPI, GPCP) cover three different periods 1979–93, 1989–98, and 1997–2002, respectively, with different horizontal resolution. The GPI precipitation data with a resolution of 5° × 5° are interpolated on a 2.5° × 2.5° mesh to match the resolution of the MSU and GPCP precipitation. A simple average is then applied to the two overlapping precipitation datasets. To assist in resolving any inhomogeneities in blending the three precipitation datasets, the National Oceanic and Atmospheric Administration (NOAA) outgoing longwave radiation (OLR) data were used.

A monsoon gyre forms a conducive environment for all tropical disturbances; not only for TCs (maximum sustained wind speed \( \leq 17.5 \text{ m s}^{-1} \)), but also for TDs (maximum sustained wind speed \( \geq 17.5 \text{ m s}^{-1} \)). Thus, both TC and TD are included in our investigation of the possible impacts of the monsoon gyre on interannual variation in their genesis frequency. The climatological-mean monthly occurrence frequencies of TC/TD (\( N_T \) in Fig. 1a) and monsoon gyres (\( N_MG \) in Fig. 1b; identification of monsoon gyres will be presented below) within the domain (0°–30°N, 120°E–180°E) of the WNP region (Fig. 1) peak during the time period July–October. In addition, the East–Southeast Asian monsoon circulation undergoes a significant change from summer to fall. An east China anticyclone forms in the fall, when the WNP subtropical high retreats eastward. Therefore, the monsoon trough migrates southward across the northern part of the South China Sea and the Philippine Sea to the region south of 15°N. For these reasons, July–August (JA) and September–October (SO) are considered as summer and fall, respectively, in the present study.

An August 1991 monsoon gyre with a life span of two to three weeks was selected by Lander (1994b) to illustrate the link of this monsoon low system to the genesis and development of three TCs (Ellie, Fred, Gladys) and two TDs (13° and 15°W). This monsoon gyre had an exceptionally long life cycle. Nevertheless, its basic characteristics and the large-scale environment presented by Lander guide the present study in the identification of monsoon gyres over the WNP region over the 1979–2002 period. A monsoon gyre in this study is identified if the following criteria are present:

1) A closed vortex with an east–west horizontal scale \( \geq 2500 \text{ km} \) and a life span \( \geq 5 \text{ days} \) that can be clearly identified in 850-mb streamline charts;
2) Daily precipitation and deep convection (daily \( \Delta \text{OLR} = 235 \text{ W m}^{-2} – \text{OLR} \)) around the south–southeast periphery of the vortex;
3) A separation of the vortex low pressure area (formed by a short wave train with adjacent surface anticyclones to the south-southwest and east-northeast)
from the landmass low pressure system over East Asia by a low-level oceanic (or eastern seaboard) high pressure zone;
4) A weak ridge/anticyclone (which may be coupled with a more complicated weather system) above the vortex; and
5) A sequence of small vortices or TDs that often forms along the south-southeast rim of the vortex.

A randomly selected case 15–28 July 1989) is shown in Fig. 2 for illustration. Presented in this figure are the 200- (Fig. 2a) and 850-mb (Figs. 2b–d) streamline charts for 28 July 1989 superimposed with trajectories (solid lines) of three TCs [(1) Judy, (2) Ken, (4) Mac] and a tropical depression [(3) TD 12] linked to this monsoon gyre and the trajectory of the monsoon gyre (dotted line). Also shown are the \( \Delta \)OLR anomalies (Fig. 2a), precipitation (Fig. 2b), and surface pressure (Fig. 2c). A well-organized monsoon gyre developed through the merger between monsoon westerlies from Indochina and trade easterlies from the tropical Pacific. This monsoon low system lay underneath a more complicated upper-level flow structure. The basic characteristics of a monsoon gyre listed above are clearly revealed from this case. To verify our selection, Japan’s Geostationary Meteorological Satellite (GMS) IR imagery superimposed with 850-mb streamlines is shown in Fig. 2d. Convective clouds and TC/TD along the south-southeast periphery of this monsoon gyre can be seen, as required in the identification criteria for a monsoon gyre. The following two modes of tropical cyclogenesis were observed by Lander (1994b): 1) small vortices forming in the southeast rim of the monsoon gyre, and 2) an acceleration of a merging TC/TD with the monsoon gyre into a large tropical cyclone. However, only the first mode operated in the 15–28 July 1989 case.

3. Impact of the monsoon gyre on TC/TD genesis
   a. Interannual variation of TC/TD genesis

   TC/TD genesis locations over the WNP region in JA and SO superimposed on the 850-mb streamline charts for these two time periods are displayed in Figs. 3a and 3c, respectively. Following the southward migration of the monsoon trough from summer to fall, TC/TD genesis locations also move southward as observed in Chen et al. (1998). Because TD genesis is included in the

In order to compare to the Chen et al. study, TC/TD genesis locations of both warm (dots) and cold (open triangles) seasons are also added on the difference of the composite 850-mb flow between cold and warm seasons, ∆V (cold − warm) for both summer (Fig. 3b) and fall (Fig. 3d).

In summer, the anomalous circulation exhibits a subtropical anomalous cyclonic cell centered south of Japan in the WNP region juxtaposed with anticyclonic cells south of 15°N and east of Japan. Positive (negative) precipitation anomalies, ∆P, are associated with the anomalous cyclonic (anticyclonic) cell. A recognizable north–south stratification of TC/TD genesis locations between cold and warm summers emerges. Like Chen et al.’s (1998) observation of TC genesis, more TC/TD genesis occurs north of 15°N during cold summers, but more south of 15°N during warm summers. The tropical anomalous anticyclonic cell becomes weaker in fall. The subtropical anomalous cyclonic circulation in summer is replaced by two anomalous cyclonic cells in fall; one centered over the South China Sea and the other in the WNP. Positive ∆P anomalies appear over the former cyclonic cell. An east–west stratification of TC/TD genesis locations across 150°E resembles that found in Chen et al. for TC genesis. TC/TD genesis are clustered more west of 150°E during cold falls, but are comparable between both sides of 150°E during warm falls.

In order to contrast TC/TD genesis frequency between warm and cold seasons in a more quantitative way, histograms of TC/TD genesis in each summer and fall with corresponding ∆SST (Niño-3) values are shown in Figs. 4a and 4d. Differences in TC/TD genesis frequency be-

1 ENSO exhibits a pronounced seasonality with its maximum development occurring during September–February and its minimum around April–June (e.g., Wright 1985; Rasmusson and Carpenter 1982). The ENSO cycle may switch from a warm winter phase to a cold phase or vice versa. In other words, the ∆SST (Niño-3) anomalies in summer/fall prior to or following a major warm (cold) ENSO event may not always be warm (cold). It is not appropriate to use the extreme ENSO event in winter to determine the warm-season climate conditions ahead of or following the winter event. For this reason Chen et al. (1998) adopted the following criteria: cold summer/fall: ∆SST (Niño-3) ≤ −0.5°C, and warm summer/fall: ∆SST (Niño-3) ≥ 0.5°C, where ∆SST (Niño-3) is the seasonal (two months in this study) mean SST departure in the NOAA Niño-3 region from its multiple-season average [generated with the NCEP SSts compiled by Reynolds (1998) and Reynolds and Marsico (1993)].
Fig. 4. TC/TD genesis frequency \((N_r)\) during (a) JA and (d) SO over the domain \((0^\circ-30^\circ N, 120^\circ E-180^\circ E)\) of the WNP. The \(N_r\) difference (b) between the regions north and south of \(15^\circ N\), and (e) between the regions west and east of \(150^\circ E\) within the analysis domain are shown. The (c) JA and (f) SO SST departures \((\Delta SST)\) from their climatological-mean values averaged over the NOAA Niño-3 region. Symbols \(W\) and \(C\) are added when \(\Delta SST\) \((\text{Niño-3}) \geq 0.5^\circ\) and \(\leq -0.5^\circ\), respectively.

Between the regions north and south of \(15^\circ N\) during summer and between the regions west and east of \(150^\circ E\) during fall are also shown in Figs. 4b and 4e. In spite of the inclusion of TDs in our analysis, a clear contrast of TC/TD genesis frequency between cold and warm seasons emerges: more (less) in the cold (warm) season. The increase (decrease) of TC/TD genesis in the cold (warm) summer comes primarily from the region north of \(15^\circ N\), but in the fall from the region west of \(150^\circ E\). McBride (1995) pointed out that two main factors...
used to determine the occurrence distribution of TC genesis are sea surface temperature (SST $\geq 26^\circ$C) and the location of the monsoon trough. The anomalous teleconnection wave train is a possible response of the summer/fall atmospheric circulation to the tropical Pacific SST anomalies. The interannual variation of the monsoon trough, which causes the interannual variation of TC genesis over the WNP, is a part of the teleconnection wave pattern. Thus, it was argued by Chen et al. (1998) that the interannual variation of tropical cyclone genesis frequency over the WNP is caused by tropical Pacific SST anomalies through the formation of an anomalous teleconnection wave train. Lander (1994b) observed that the monsoon gyre often appears over the monsoon trough and rainfall/deep convection occurs along the gyre’s south-southeast periphery (a preferred region of TC/TD genesis). This observation leads to the following questions:

1) Does monsoon gyre activity over the WNP undergo an interannual variation following that of the monsoon trough?

2) What is the role played by the monsoon gyre in the interannual variation of TC/TD genesis over the WNP?

These two questions which constitute the theme of this study will be explored and answered in section 3b.

b. Interannual variation of the monsoon gyre and its impact on TC/TD genesis

After identifying all monsoon gyres during the period 1979–2002, the following strategy was adopted to portray their activity. The location of monsoon gyre centers was noted when the genesis of a TC/TD linked to a gyre occurred. The seasonal-mean 850-mb streamline charts superimposed with the locations of monsoon gyre centers in both seasons (JA and SO) are shown in Figs. 5a and 5c, respectively. Recall that genesis locations of TCs/TDs shown in Figs. 3a and 3c are generally clustered along the monsoon trough in both the JA and SO periods. As will be shown later, a large percentage of TC/TD geneses shown in Figs. 3a and 3c appears in the south-southeast periphery of the monsoon gyre, so it is not surprising to see that centers of identified monsoon gyres cluster north of $15^\circ$N in JA and along $15^\circ$N in SO.

In order to explore the interannual variation of monsoon gyre activity, the centers of these gyres during warm and cold seasons are marked by dots and open triangles, respectively, on the difference of the 850-mb flow $\Delta V$ (850 mb) between these two extreme warm seasons (Figs. 5b and 5d). It is inferred from the $\Delta V$ (850 mb) streamline charts that the JA monsoon trough shifts northward due to the anomalous cyclonic circulation north of $15^\circ$N during cold seasons, and southward (with an eastward extension) due to the anomalous cyclonic circulation south of $15^\circ$N during the warm seasons. In SO, the location of the monsoon trough is affected by the anomalous circulation in the WNP region in a way similar to that in JA. A distinct NW–SE stratification of monsoon gyre centers emerges from Figs. 5b and 5d. It is clear that monsoon gyre activity is remarkably affected by the interannual variation of the WNP monsoon circulation.

The interannual variation of monsoon gyre activity caused by the WNP monsoon circulation changes may be quantified by the accumulated life cycles of monsoon gyres in every year (JASON). The life span of every identified monsoon gyre is marked by a solid line of...
different length in Fig. 6a. Although Fig. 6a hints that monsoon gyre occurrence is more (less) frequent in cold (warm) seasons, the relationship is more quantitatively clear in the histogram of accumulated life spans of monsoon gyres in each year (Fig. 6b). Evidently, monsoon gyres occur either more frequently or exist longer in cold than in warm years. If the monsoon gyre is a facilitator of TC/TD genesis, the longer (shorter) life span and greater (less) occurrence of monsoon gyres would enhance (reduce) the probability of TC/TD genesis. This hypothesis suggests a possible link between interannual variations of TC/TD genesis frequency and monsoon gyre activity.

Thus far, two important aspects of WNP TC/TD genesis are revealed from our analysis. First, the accumulated life spans of monsoon gyres every year (Fig. 6b) and the total WNP TC/TD genesis frequencies of the combined JA and SO periods (Figs. 4a and 4d; including those related and unrelated to monsoon gyres) seem to be correlated to some extent (with a correlation coefficient of 0.61). Second, the north–south and east–west stratifications of TC/TD genesis locations (Figs. 3b and 3d) and the centers of monsoon gyres (Figs. 5b and 5d) in cold and warm seasons are relatively consistent. Because TC/TD genesis and development in the WNP frequently occurs over the active convection/rainfall region along the south-southeast periphery of monsoon gyres, the two findings presented here support the hypothesis stated above. To strengthen our argument, dates of TC (shown by ◦) and TD (shown by ◆) genesis are marked in Fig. 6a. The total number of TC/TD genesis events and development linked to monsoon gyres in both seasons (Figs. 6c and 6d) and the combination of both (Fig. 6e) are shown by histograms in the right column in Fig. 6. The total TC/TD genesises over the WNP region in each season are also indicated by dashed histograms for reference.

As shown in Fig. 6e, the percentage of WNP TC/TD genesis and development linked to monsoon gyres is about 70% of the total WNP TC/TD genesis. This statistic provides a clear confirmation of Lander’s observation. However, can we quantify the impact of monsoon gyres on the TC/TD genesis and development? As shown in Fig. 6b, the total monsoon gyre life spans each year ($D_{MG}$) are longer (shorter) during cold (warm) seasons. The average value ($\bar{D}_{MG}$) and standard deviation ($\sigma_{D_{MG}}$) of $D_{MG}$ are 57.3 and 11.3 days, respectively. Since $\sigma_{D_{MG}}/\bar{D}_{MG} \approx 20\%$, $D_{MG}$ apparently undergoes a significant interannual variation. If the monsoon gyre is a facilitator of TC/TD genesis and development, it is likely that the correlation between $D_{MG}$ and $N_{FG}$, $\gamma_{D_{MG},N_{FG}}^{\text{JA-SO}}$, should be significant. As expected, the value of $\gamma_{D_{MG},N_{FG}}^{\text{JA-SO}}$ is 0.89. This statistic, coupled with the modulation of the anomalous monsoon circulation by monsoon gyre activity over the WNP shown in Figs. 5b and 5d, substantiates the hypothesis that enhanced (suppressed) monsoon gyre activity results in the enhancement (suppression) of the TC/TD genesis and development over the WNP region.

Finally, a comment on the difference between $N_F$ and $N_{FG}$ is in order. The ratio ($N_F - N_{FG}$)/$N_F$ is about 29%. In other words, less than one-third of WNP TC/TD genesises are not related to monsoon gyres. As shown in Fig. 7, interannual variations of $N_{FG}$ ($=N_F - N_{FG}$) in both seasons do not exhibit any correlation with $\Delta$SST (Niño-3). It was observed by Chen et al. (1998) that the interannual variation of WNP TC genesis is caused by tropical Pacific SST anomalies through the interannual variation of the WNP monsoon circulation. As revealed from the high correlation between $N_{FG}$ and $D_{MG}$, it is more accurate to state that the modulation of WNP TC/TD genesis by tropical Pacific SST anomalies is through the impact of these SST anomalies on monsoon gyre activity.

4. Concluding remarks

The monsoon trough of the western North Pacific (where monsoon southwesterly winds lie equatorward of Pacific trade wind flow) often becomes organized as a monsoon gyre rather than an elongated trough. As observed by Lander (1994b), precipitation/deep convection appears along the south-southeast periphery of monsoon gyres. The downstream region of convection becomes a preferred region for TC/TD genesis in the WNP. In response to tropical Pacific SST anomalies associated with the ENSO cycle, Chen et al. (1998) found that the tropical WNP monsoon circulation exhibits a north–south dipole of east–west elongated cyclonic–anticyclonic anomalous circulation cells in summer and slightly NE–SW-oriented cyclonic–anticyclonic anomalous cells in fall. These anomalous circulations enhance (weaken) TC genesis frequency north of 15°N during cold (warm) summers and west (east) of 150°E during cold (warm) falls. Because the monsoon gyre is a synoptic-scale disturbance, the impact of tropical Pacific SST variations on WNP TC/TD genesis frequency should be reflected by monsoon gyre activity in the tropical WNP monsoon system.

Using 6-h JMA TC and JTWC TD track records and NCEP–NCAR reanalysis data, an effort was made to explore interannual variations in monsoon gyre and TC/TD genesis activity in response to tropical Pacific SST anomalies. Two major findings were obtained.

1) Approximately 70% of WNP TC/TD genesis/development is linked to the monsoon gyre.
2) The interannual variation of TC/TD genesis/development related to the monsoon gyre is highly correlated with that of the monsoon gyre activity (which is out of phase with that of the NOAA Niño-3 SSTs).

These findings strongly support the hypothesis that tropical Pacific SST variations impact interannual variations of WNP TC/TD genesis/development activity through the modulation of monsoon gyre activity.
Despite a significant correlation between interannual variations of WNP TC/TD genesis/development and monsoon gyre activity observed by the present study, some basic questions concerning the relationship between them and the tropical Pacific SST anomalies still need to be answered.

1) Why does the southeast rim along a monsoon gyre become a preferred region for TC/TD genesis? Perhaps, the strong southerlies of the confluent flow along the south-southeast rim of a monsoon gyre advect small planetary vorticity northward (i.e., $\beta$ advection) to generate a negative vorticity tendency...
in the downstream. Consequently, positive vortex stretching is induced to counteract the β advection, and convergent flow is generated to maintain convection/rainfall along the southeast rim of a monsoon gyre. A diagnosis of the vorticity dynamics suggested here may answer the question.

2) Because a monsoon gyre provides a favorable environment for TC/TD genesis/development, under what synoptic conditions can a monsoon gyre form? Holland (1995) suggested that the formation of monsoon gyres is possibly related to the 30–60-day monsoon mode. How does the 30–60-day monsoon mode affect the formation of monsoon gyres, and in turn TC/TD genesis activity? The monsoon life cycle over the (South China Sea) SCS–NWP region reflects the intraseasonal variations in the monsoon westerlies (Chen and Chen 1995). Because the merger of monsoon westerlies and Pacific trade winds occurs in the tropical WNP region, can monsoon gyres form more (less) often during active (break) monsoon period? A contrast between the monsoon life cycle in the SCS–WNP region and WNP TC/TD genesis activity may provide the answer to the above question.

3) As shown in Fig. 6, monsoon gyre occurrence and TC/TD genesis/development undergo a highly correlated interannual variation. If the formation of monsoon gyres can be affected by the intraseasonal monsoon mode as indicated in question 2), can interannual variations of monsoon gyres and WNP TC/TD genesis activity follow that of the 30–60-day monsoon mode? Lau and Chan (1986) showed that the eastward propagation of the 30–60-day mode was modulated by the ENSO cycle. Can this modulation of the intraseasonal mode modify the monsoon gyre and TC/TD genesis activity? A new understanding of the interannual variation of TC/TD genesis may be derived from study of this downscale process.

Additional research is ongoing for answers to these questions, and results of this effort will be reported in the near future. It is hoped the additional research will lead to a better understanding of WNP TC/TD genesis activity.

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REFERENCES


Nitta, T., 1987: Convective activities in the tropical western Pacific and their impact on the Northern Hemisphere summer circula-


