# Multiscale Interaction in the Western North Pacific Monsoon with Emphasis on Tropical Cyclone Formation

吳宜昭 林和
國立台灣大學大氣科學系暨研究所

## Abstract

This study examines the multiscale influences on tropical cyclone (TC) formation in the western North Pacific Monsoon (WNPM) region. Emphasis is placed on the roles of monsoon trough, monsoon confluence zone, tropical intraseasonal oscillation (TISO), and the synoptic-scale waves, in enhancing TC formation. The contributions from interactions among these scales are also discussed. As this study emphasizes the predominance of monsoon system over multiscale motions in WNP, how significantly WNP TC formations are associated with these four patterns are evaluated first on the basis of sub-seasonal variation, then on the interannual variation due to ENSO.

Key words: multiscale interation, western North Pacific monsoon, Tropical cyclone formation.

## I. Introduction

The WNPM is remarkably endowed with rich spectrum of motions. It spans from mighty Pacific climate systems like ENSO and the Pacific Decadal Oscillation (PDO), to the fully energized synoptic eddies; e.g., easterly wave and tropical cyclones. Amid this spiral chaos of scale interaction and cascade, the Asian-Pacific monsoon system, particularly during the boreal summer, plays the dominant role. Thus the multiple scale interaction can be nudged into a framework that basically follows what coined as the Fast Annual Cycle (FAC, LinHo and Wang, 2002) framework.

The classic work of Gray (1968) established six environmental features as favorable conditions for tropical cyclone formation. The large-scale circulation variability can change these parameters, except the Coriolis parameter, in various time scales, which in turn influences the TC formation to different degrees. Under the framework of FAC this study investigates how significantly the large-scale circulation, from a wide range of scales, modulates WNP TC formation.

The large-scale troughs carrying strong low-level vorticity are prolific breeders of TCs. In the boreal summer, particular in the late summer from late July to early September, the deep monsoon trough is where numerous TCs form. When WNPM ends and the western Pacific Subtropical High (WPSH) retreats to the subtropics, the autumn trough, a shear line between the penetrating easterly and the residual southwesterly, prevails south of 15°N over southern South China Sea and the Philippine Sea to generate autumn TCs.

The confluence zone between monsoon southwesterly and easterly is another region where TCs frequently form. Such patterns are common in both early summer, when the monsoon southwesterly and easterly along the southern frank of WPSH converge near Philippine Sea to flow northwards, and in late summer, when the strong cross-equatorial flow and monsoon southwesterly meet trade winds at the eastern end of monsoon trough. A range of scale interactions tend to occur here, which generates favorable conditions for TC formation. (Holland 1995). Moreover, the energy accumulation as the westward (or eastward) propagating Rossby waves approach the confluence region (Chang and Webster, 1990) may lead to disturbance growth and TC formation.

The abovementioned interaction between synoptic-scale waves and large-scale confluence is substantially modulated by TISO. The westward-moving synoptic-scale disturbances in western North Pacific (WNP) and their associations with TC formation have been pointed out in many studies (Lau and Lau 1990; Chang et al. 1996; Sobel and Bretherton 1999; Wheeler and Kiladis 1999; Dickinson and Molinari, 2002; and many others). The northwestward-moving waves, usually emanating from central tropical Pacific, have a frequency about 10 days (Wheeler and Kiladis 1999; Dickinson and Molinari, 2002). These quasi-biweekly waves (OBWs) are not confined in the equatorial wave guide and their beams have a northward component. Thus an area of wave duct appears to exist (Webster and Chang 1988). The zone where the zonal winds converge, causing disturbances more compact, may excite further disturbance growth and its evolution into a TC (Holland 1995, Sobel and Bretherton 1999, Kuo et al. 2001).

Some studies have investigated the association between TC formation and large-scale circulation features (Briegel and Frank 1997; Ritchie and Holland 1999). In comparison with above works, this study emphasizes the predominance of monsoon system in the WNP TC active regions. Hence the sub-seasons of the WNPM are the basis on which this study analyzes and compares the significance of large-scale influences on TC formation. In addition to the sub-seasonal variability, the interannual variations due to ENSO are also foci of the work.

## II. Data and Method

### 1. Data

This study is performed over a 24-year period from 1979-2002. The historical records of WNP TCs and tropical depressions include the 6-hourly best track archives from Joint Typhoon Warning Center. The genesis time and location of a TC, regardless of its maximum intensity during its lifetime, are defined as the time and location which appear in the starting record of the cyclone. The dynamical fields include daily data from National Centers of Environmental Prediction–National Center for Atmospheric Research (NCEP-NCAR) reanalysis (Kalnay et al., 1996) with 2.5° latitude-longitude resolution. Also used are daily outgoing longwave radiation (OLR) data on 2.5° latitude-longitude grids.

### 2. Differentiation of three sub-seasons

The length of each sub-season is not fixed but varies in each year. The beginning of early summer is marked by the onset of SCS monsoon (Wang et al. 2004). The abrupt northward movement of WPSH and convection over WNP at late July marks the start of late summer. When the WNP convection suddenly weakens and the trade winds penetrate into Indochina Peninsula, the late summer ends and autumn begins. The subjective analysis by authors determines the onset dates of these two sub-seasons. The end of November, which is approximately the end of most TC activity, is chosen to be the end of autumn. Hence these three sets of onset dates plus the end of November determine the start and end of each sub-season in each year.

### 3. Defining and Identifying major large-scale patterns

Monsoon trough/autumn trough, monsoon confluence region, TISO, and QBW are four major circulation characteristics to be identified. The former two are defined based on the sub-seasonal mean of 850hPa flow. The monsoon trough/autumn troughs are defined where the 850hPa relative vorticity are high. The confluence zones are defined where the wind flows eastward (westward) to the west (east) of TC genesis site. The identification of TISO is based on the 20-80-day filtered 200hPa velocity potential and OLR, and that of QBW on the 7-12-day filtered 850hPa wind.

## III. Results and Discussion

### 1. Sub-seasonal variability

Climatologically, in early summer, the lower level circulation of WNPM features a confluent zone between the zonally opposing trade winds and monsoon southwesterly. While some TCs form in the confluence zone, others along the weak monsoon trough (upper panels of Fig. 1 and Fig. 2). In late summer, a deep, much stronger monsoon trough extends southeastwards from Southeast Asia to WNP. The high SST (not shown) and background vorticity in deep monsoon trough provides favorable conditions for TC genesis. A large proportion of TCs form in the monsoon trough. The confluence zone to the east of monsoon trough also contributes to some TC formation (middle panels of Fig. 1 and Fig. 2). The autumn trough, which characterizes the large-scale pattern in boreal autumn, suppressed south of 15°N and maintained by the Maritime Continent monsoon, generates most of autumn TCs on both sides of Luzon, Philippines (bottom panels of Fig. 1 and Fig. 2).

In summary, monsoon confluence zone, monsoon trough, and autumn trough play leading roles in regulating the WNP TC formations in early summer, late summer, and autumn, respectively. Comparing to the mean flow patterns, the TISOs and QBWs make equivalent contribution to TC formations in late summer, but less in early summer and in autumn (results not shown here).

**2.** Interannual variability

ENSO phases significantly influence the WNPM strength and the WNP TC formation. Four years are chosen to illustrate the influences of developing warm ENSO events on WNP TC formations. Included are year 1982, 1987, 1994, 1997 (called Nino(0) years hereinafter). Another four years, 1983, 1984, 1988, 1998 (called Nino(1) hereinafter) are to be compared with Nino(0) years. The composites of 850hPa wind fields of Nino(0) and Nino(1) years, with respect to each sub-season, are shown in Fig. 3. In Nino(0) summers, the intensifying cross-equatorial flow, which curves over New Guinea and Borneo, and the tropical westerly collaborate to strengthen the summer monsoon trough. The enhancement is particular strong in the late summer. Along with the eastward extension of monsoon trough or autumn trough, the zonal extent of WNP TC formation sites also increases. In Nino(1) summers, however, monsoon troughs are suppressed and the low level flow of WNPM remain a confluent zones instead of monsoon troughs. WNP TCs no longer form in a zonally elongated patch, as in Nino(0) summers, but spread over a larger region around the low level confluence zone. The contrast remains strong in autumns. In Nino(0) autumn, with the development of ENSO, the autumn trough, and so do the TC formations, extends far into central Pacific. On the other hand, in Nino(1) autumns the stronger trade winds restrict the autumn troughs within SCS and Philippine Sea. While some TCs still form within the autumn trough, some form farther north at higher latitudes.

The phases of ENSO events influence not only the large-scale monsoon mean flows, but also the interaction between TISO and QBW. The regulation is season-dependent. The comparison between year 1987 and 1988 serves to illustrate the differences. During the boreal summer and fall in year 1987 (left panel of Fig. 4), in WNP near 10°N, active disturbances, shown as alternating northerly and southerly in 850hPa wind fields, propagate westwards and northwards (the horizontal spatial diagram identifying the northward movements of QBW is not shown here) on a 7-12-day period. These fast northwestward-propagating waves are modulated by eastward-moving wave packets, the TISOs. Closely associated with these convectively active disturbances are TC formations. For example, the formations of TC 5, 6, and 8 coincide well with QBWs, which originate near 160°E and precede TC formations. The activity of these QBWs are interrupted by several breaks and grouped into four wave packets, which appear to occur on a 20-80-day time scale. In comparison with late summer, activities of TISOs, QBWs, and TCs in autumn are no longer as active. In contrast, in year 1988 (Fig. 4, right panel), the TISOs and associated QBWs weaken a lot in late summer, but regain their strengths in autumn. Such differences between Nino(0) and Nino(1) years are also common in other cases.

To summarize the contribution from these multiscale interactions to TC formations, we identify and count the existence of abovementioned four major large-scale patterns when there are TC formations. The preliminary analysis (results not shown) shows that ENSO phases have very little influences on the annual total of TC formation in WNP, which is also pointed out in Lander (1994). The sub-seasonal total is, however, more significantly modulated by the ENSO phases. The ratio of TCs form in autumn to those in summer increases from 0.5 in Nino(0) years to 1.2 in Nino(1) years. The contrast in TISO strength between Nino(0) late summer and Nino(1) autumn primarily accounts for such variation. Overall, in early summer, two monsoon mean flow patterns, monsoon trough and confluence region, dominate the TC formation in response to ENSO variation. The modulation by TISO is secondary. In late summer, strong (weak) monsoon trough and strong (weak) TISO are equally important in increasing (decreasing) WNP TC formation in Nino(0) (Nino(1) )years. In autumn, On the other hand, the influence of TISO outweighs that of autumn trough to contribute to less (more) TC formation in Nino(0) (Nino(1)) years.

The preliminary analysis shows close association between complicated multiscale interaction between WNPM and WNP TC formation. A number of important works are currently underway. The most essential one is to quantify the relative importance of different scales in regulating TC formations. Other critical issues remain to be uncovered. For example, how ocean dynamics store climate memory across seasons. The feedback of TC to monsoon variation itself also prompts further study. Our goal is to combine both monsoon and TC studies to give a holistic view of WNP scale interaction.

## References

Briegel, L. M., and W. M. Frank, 1997: large-scale influences on tropical cyclogenesis in the western North Pacific. *Mon. Wea. Rev.*, **125**, 1397-1413.

Chang, C.-P., J. M. Chen, P. A. Harr, and L. E. Carr, 1996: Northwestward-propagating wave patterns over the tropical western North Pacific during summer. *Mon. Wea. Rev.*, **124**, 2245-2266.

Chang, H.-R., and P. J. Webster, 1990: Energy accumulation and emanation at low latitudes. Part II: nonlinear response to strong episodic equatorial forcing. *J. Atmos. Sci.*, **47**, 2624-2644.

Dickinson, M., and J. Molinari, 2002: Mixed Rossby-gravity waves and western Pacific Tropical cyclogenesis. Part I: synoptic evolution.. *J. Atmos. Sci.*, **59**, 2183-2196

Gray, W. M., 1968: Global view of the origin of tropical disturbances and storms. *Mon. Wea. Rev.*, **96**, 669-700.

Holland, G., J., 1995: Scale interaction in the western Pacific monsoon. *Meteorol. Atmos. Phys.*, **56**, 57-79.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-Year Reanalysis Project. *Bull. Amer. Meteor. Soc.*, **77**, 437-471.

Kuo, H.-C., J.-H. Chen, R. T. Williams, and C.-P. Chang, 2001: Rossby waves in zonally opposing mean flow: behavior in northwest Pacific summer monsoon. *J. Atmos. Sci.*, **58**, 1035-1050.

Lander, M. 1994: An exploratory analysis of the relationship between Tropical Storm Formation in the western North Pacific and ENSO. *Mon. Wea. Rev.*, **122**, 636-651.

Lau. K.-H., and N.-C. Lau, 1990: Observed structure and propagation characteristics of tropical summertime disturbances. *Mon. Wea. Rev.*, **118**, 1888-1913.

LinHo, and B. Wang, 2002: The time-space structure of the Asian-Pacific summer monsoon – a fast annual cycle view. *J. Climate*, **15**, 2001-2019.

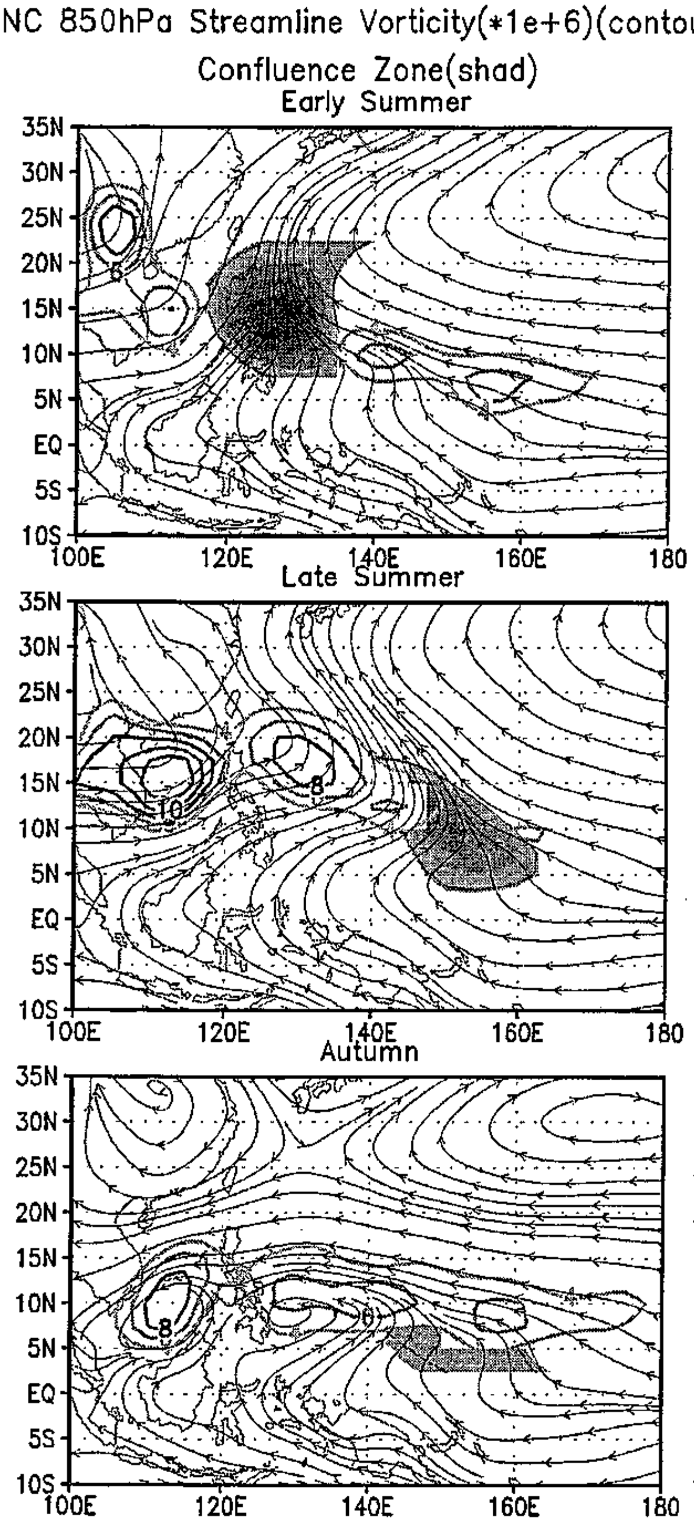
Ritchie, E. A., and G. J. Holland, 1999: Large-scale patterns associated with tropical cyclogenesis in the western Pacific. *Mon. Wea. Rev.*, **127**, 2027-2043.

Sobel, A. H., and C. S. Bretherton, 1999: Development of synoptic-scale disturbances over the summertime tropical northwest Pacific. *J. Atmos. Sci.*, **56**, 3106-3127.

Wang, B., LinHo, Y. Zhang, and M.-M. Lu, 2004: Definition of South China Sea monsoon onset and commencement of the East Asia summer monsoon. *J. Climate*, **17**, 699-710.

Webster, P., and H.-R. Chang, 1988: Equatorial energy accumulation and emanation regions: Impacts of a zonally varying basic state. *J. Atmos. Sci.*, **45**, 803-829.

Wheeler, M., and G. N. Kiladis, 1999: Convectively coupled equatorial waves: analysis of clouds and temperature in the wavenumber-frequency domain. *J. Atmos. Sci.*, **56**, 374-399.



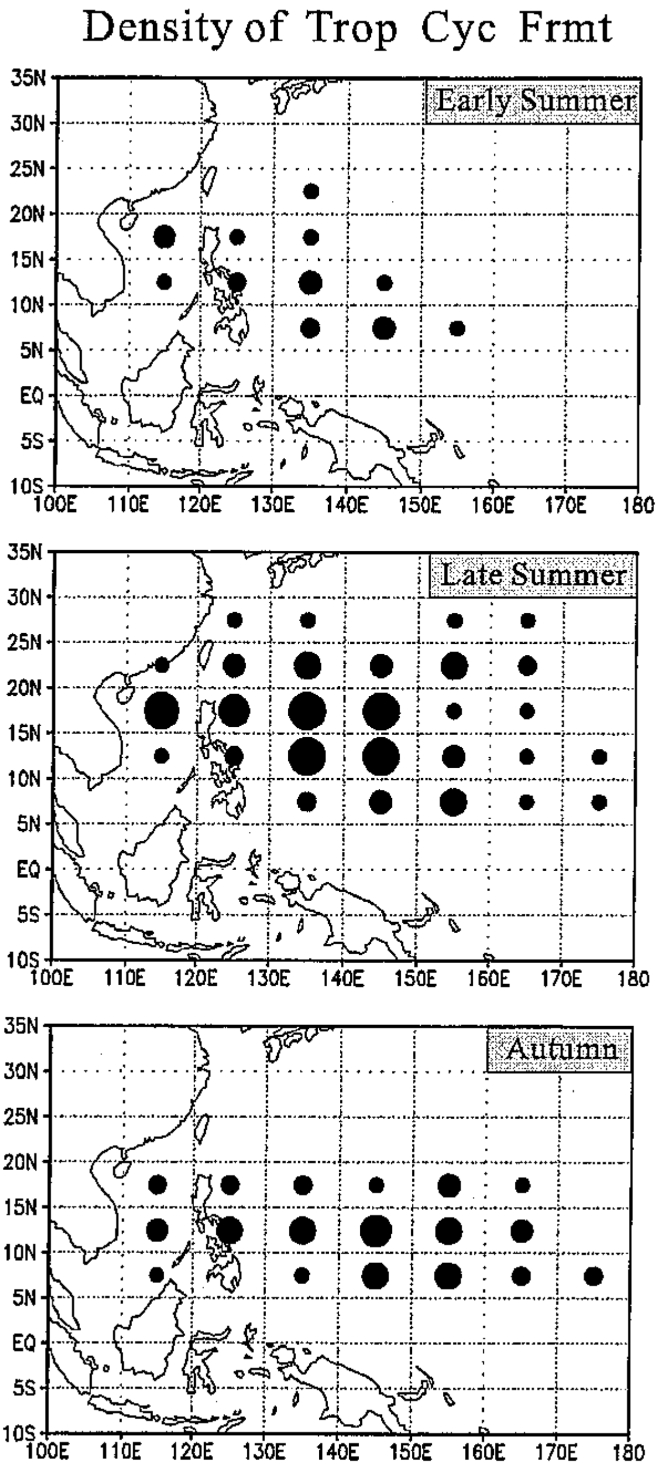
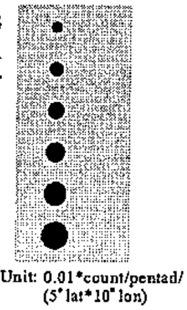


Fig. 1. The climatology of 850hPa streamlines, vorticity (contour), and confluence zone (shaded), derived from 1979~1998 NCEP Reanalysis data, are averaged over three sub-seasons, early summer (upper, pentad 25~39), late summer (middle, pentad 40~51), and autumn (bottom, pentad 52~67). For each grid point, it is zonally confluent if the product of the zonal wind to its west and to its east is negative. So only negative values of the wind product are shaded. The minimum vorticity contour value is $4x10^{-6}s^{-1}$, and the interval is $2x10^{-6}s^{-1}$.

Fig. 2. Divided into sub-seasons as Fig.1, the climatological tropical cyclone formation rates over 1959~1998 are shown in above panels. The size of sphere is proportional to tropical cyclone formation rate (unit: 0.01*formations/pentad/5degree latitude x 10 degree longitude).



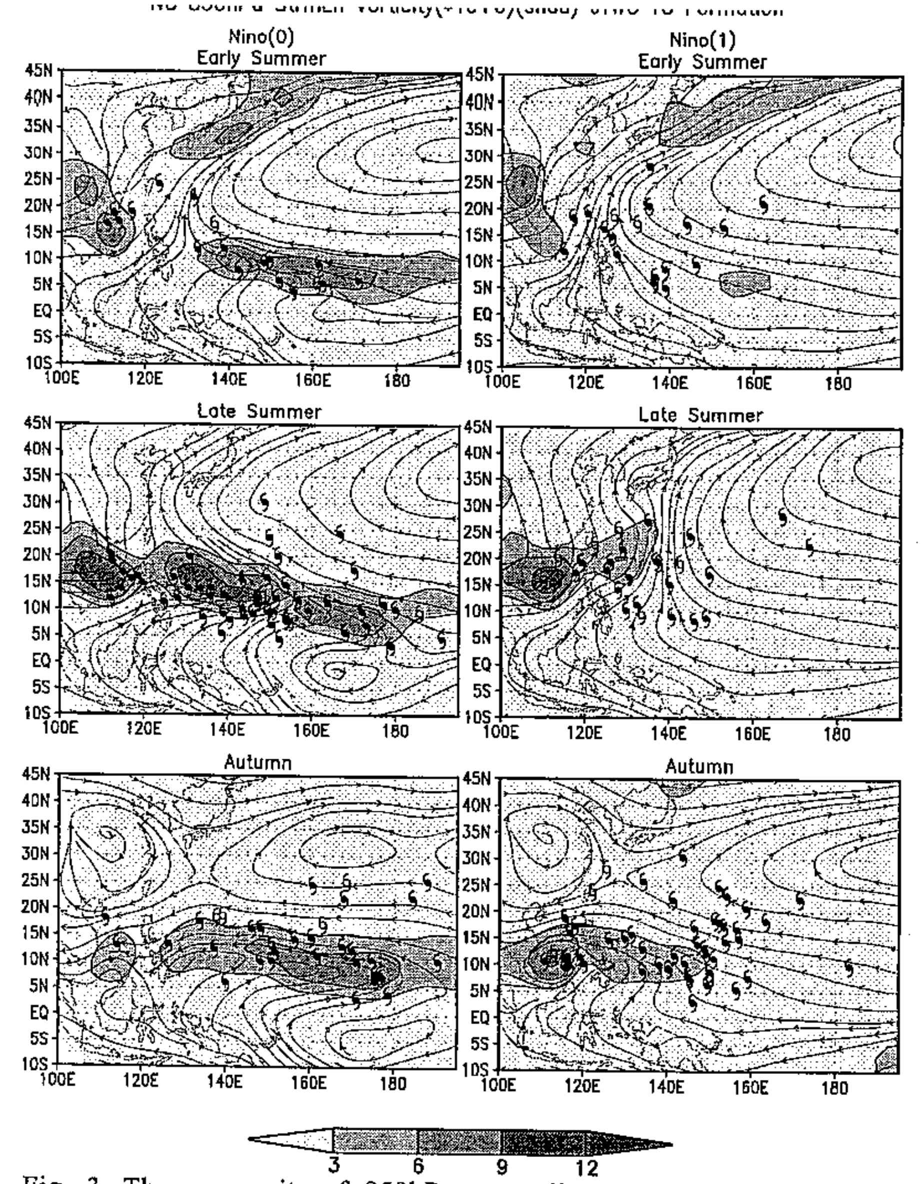


Fig. 3. The composite of 850hPa streamlines, vorticity (shaded), and tropical cyclone formation locations in early summer (upper), late summer(middle), and autumn (bottom). The left column shows the years when ENSO are developing (Nino(0) years), the right column years after ENSO peaks (Nino(1) years). Only areas with vorticity larger than$3\times10^{-6}s^{-1}$ are shaded. Both the minimum contour value and the contour interval are $3\times10^{-6}s^{-1}$.

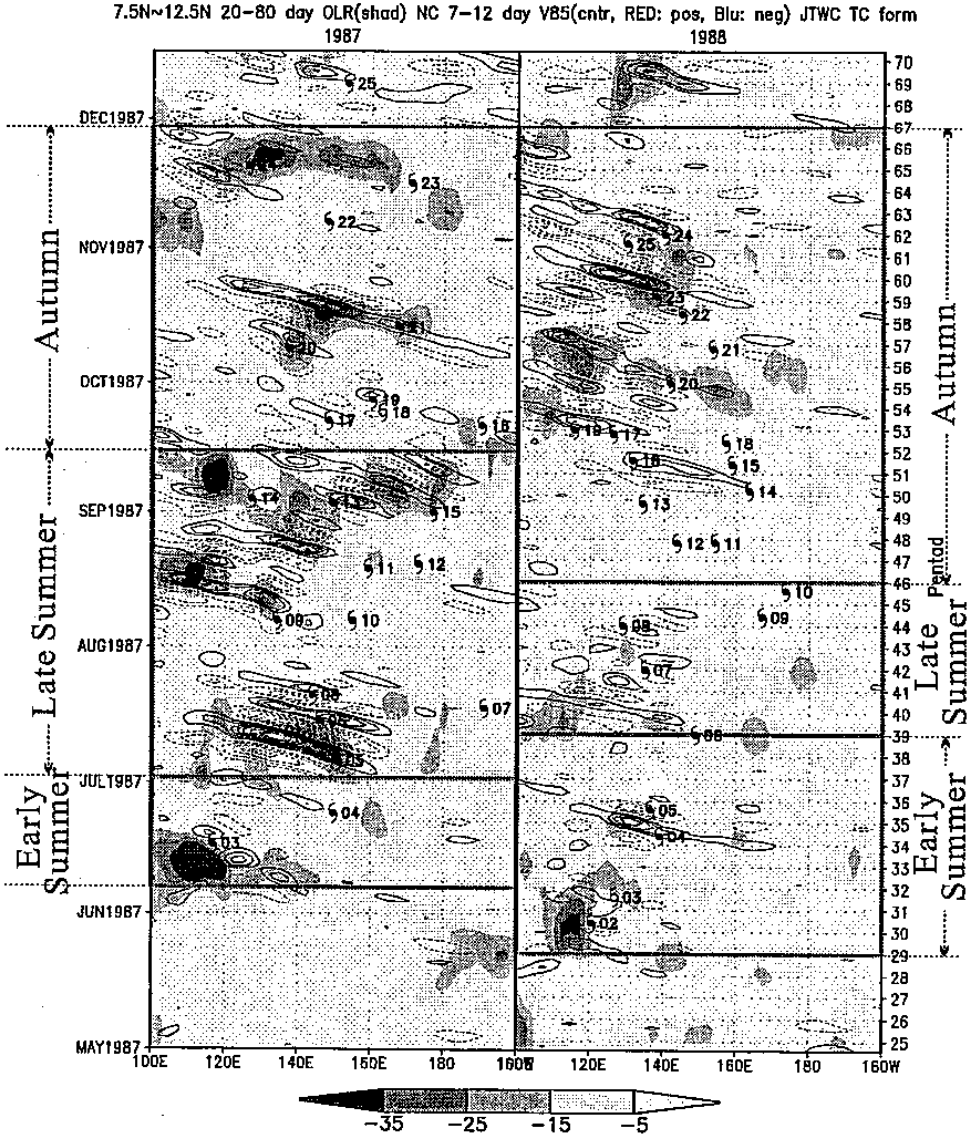


Fig. 4. Longitude-time diagrams of the 7-12-day filtered 850hPa meridional wind (contoured) and the negative phase of 20-80-day filtered OLR (shaded) at 10N for 1987 (left panel) and 1988 (right panel). Red, solid contours are southerly, and blue, northerly. Superposed on the diagram are tropical cyclone formation locations (regardless of formation latitudes). Based on highest intensity during the lifetime of each tropical cyclone, two different marks are used to distinguish tropical storms from tropical depressions.