

SIXTH INTERNATIONAL WORKSHOP on TROPICAL CYCLONES

Topic 4.1 : Variability of Tropical Cyclone Activity/Intensity on Intraseasonal and Interannual Scales

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Topic 4.1 reviews the current status of the understanding on variability of tropical cyclone (TC) activity/intensity on intraseasonal to interannual time scales around the globe. Annually, approximately 80–90 TCs occur over the tropical oceans (Neumann 1993). The TC activities depend on thermodynamic parameters (e.g., sea surface temperature (SST), atmospheric stability, and mid-tropospheric moisture) and dynamic parameters (e.g., low-level vorticity, vertical wind shear, and upper-tropospheric momentum flux convergence) (Gray 1979). In many cases, thermodynamic parameters are closely linked with each other in the tropics; the atmosphere overlying high SSTs tends to be humid, and humid air with high atmospheric temperature inevitably becomes unstable.

Over the tropical oceans prone to frequent TCs, the thermodynamic factors for TC formation are most often satisfied. Also, the dynamic parameters—positive low-level vorticity and weak vertical wind shear—give rise to environments favorable for the generation of TCs. In the case of changes in the large-scale circulation in the tropical oceans, the thermodynamic and/or dynamic parameters may be modified. These modifications, in turn, may alter the TC activity/intensity.

The variation of the TC activity is to some extent associated with the El Niño–Southern Oscillation (ENSO), quasi-biennial oscillation (QBO), Arctic Oscillation (AO), North Atlantic Oscillation (NAO), Antarctic Oscillation (AAO), Madden–Julian oscillation (MJO), etc., depending on ocean basins. Subsequently, the discussion will involve several ocean basins such as the western North Pacific (WNP), the North Atlantic (NA), the eastern and central North Pacific (ECNP), the Indian Ocean (IO), and Australia and South Pacific (ASP).

a) Western North Pacific (WNP)

A pronounced interannual variability exists in the TC activity in the WNP in connection to the ENSO events; the active genesis region of the TC moves both eastward and toward the equator, the life span and probability of the intense TC increase, and TCs recurve more often and tend to recurve farther eastward during the warm phase of ENSO (e.g., Chan 1985; Lander 1994; Chen *et al.* 1998; Chan 2000; Chia and Ropelewski 2002; Wang and Chan 2002; Camargo and Sobel 2005). The increase (decrease) in the TC activity in the southeast (northwest) quadrant of the WNP during El Niño years can be explained by the eastward shift in the preferred genesis location and the increased northward steering flows. The opposite is true during La Niña years. There is also a notable frequency reduction in TC formation in the summer following of the El Niño year, corresponding to a longitudinal shift of the Walker circulation (Chan 1985; Wu and Lau 1992; Chan 2000).

The cross-spectral analysis demonstrated that two time series of the stratospheric QBO and TC activity in the WNP are almost in phase during the 28-month period (Chan 1995); the westerly phase of the QBO corresponds to a larger number of TCs. The QBO–TC relation would be a result of the decrease

in the upper-tropospheric vertical shear over the tropics during the boreal summer associated with the westerly phase of the QBO. However, this relationship did not hold true during ENSO years.

Ho *et al.* (2005) suggested that the TC activity in the WNP is also influenced by the large-scale circulation in the Southern Hemisphere (e.g., AAO) through changes in convection activity along the Intertropical Convergence Zone in the western equatorial Pacific. In the positive phase of AAO (relative to its negative phase), two anomalous highs—a huge anticyclone in southeastern Australia and a relatively weak anticyclone in the East China Sea—develop over the western midlatitude Pacific in both the hemispheres. A statistically significant alteration in TC activity related to the AAO variations is observed over the WNP. This change has primarily resulted due to the increase in TC formation over the eastern Philippine Sea.

The number of TCs in the WNP and TC landfalls in China is seen to negatively correlate with the Tibetan Plateau snow cover during the preceding winter and spring (Xie *et al.* 2005). When the Tibetan Plateau snow cover exceeded normal levels, fewer TCs were formed in the WNP and made landfall in China and vice versa. This can be understood by the response of the western Pacific subtropical high to the snow-modulated land surface thermodynamic processes over the Tibetan Plateau.

On an intraseasonal time scale, the period of active TC genesis tends to form a cluster over a period of 2–3 weeks, followed by a comparable period of inactive TC genesis (Gray 1979). Hence, by combining both the active and inactive periods, the TC activity seems to fluctuate over a 4–6 week period, i.e., the periodicity on intraseasonal time scale. Over the WNP, the TC activity tends to be strong during the MJO convective period (e.g., Nakazawa 1986; Hartmann *et al.* 1992; Liebmann *et al.* 1994). However, the ratio of intense systems (i.e., tropical storms and typhoons) to weak systems (i.e., tropical depressions) seems nearly constant regardless of the convective and/or dry periods (Liebmann *et al.* 1994).

The enhanced TC activity during the MJO convective period can be explained by low-level barotropic wave dynamics over monsoon confluent regions (e.g., Holland 1995; Sobel and Maloney 2000; Maloney and Hartmann 2001; Maloney and Dickinson 2003). The time-mean values of the barotropic wave-activity flux at 850 hPa increases during the westerly phase of the MJO. When an anomalous westerly phase occurs in the lower tropospheric circulation field, a barotropic convection process from the mean flow to the eddy kinetic energy is activated; this process is associated with the strong low-level convergence of the monsoon flow. Thus, eddies grow such that a favorable condition for TC genesis is provided. The opposite is true during an anomalous easterly phase. Further, Kim *et al.* (2006) found that TC tracks largely depend on the MJO phases; when the MJO-related convection center locates in the equatorial Indian Ocean (tropical WNP), TC passages migrate eastward (westward) due to changes in both the major genesis region and prevailing large-scale steering flows.

There are also efforts to understand TCs variability on an intraseasonal time scale by classifying their tracks in connection with large-scale circulation. Hodanish and Gray (1993) stratified four patterns according to the difference in the recurving process—sharply recurving cyclones, gradually recurving cyclones, left-turning cyclones, and nonrecurving cyclones. Harr and Elsberry (1991, 1995a, b) elucidated that certain pattern of TC tracks can be distinguished based on the anomalous large-scale circulation. Their patterns were classified into three classes—straight, recurving south (recurving TCs that formed south of 20°N), and recurving north (recurving TCs that formed north of 20°N). Lander (1996) also considered categorizations of TC motion which he classified into four major patterns—straight moving, recurving, north-oriented, and staying—in the South China Sea.

Kim *et al.* (2005) investigated the variation of the summertime TC activity over East Asia using the empirical orthogonal function analysis and found a pronounced west-east oscillation between Korea and Japan. Anomalous atmospheric flows connected to the west-east oscillation are an enhanced anticyclonic (cyclonic) circulation centered on Japan when the TC activity is high over the south of Korea (southeast of Japan), showing an equivalent barotropic structure in the whole troposphere.

b) North Atlantic (NA)

In many cases, TCs in the NA are developed associated with African easterly waves (e.g., Landsea and Gray 1992; Goldenberg and Shapiro 1996; Thorncroft and Hodges 2001). The activity of African easterly waves intensifies (weaker) when the rainfall amount over the western Sahel region exceeds (below) normal. Namely, TC activity in the NA seems to be increased during wet years of the western Sahel. Based on the statistics of the tracking of vorticity centers connected to African easterly wave activity, Thorncroft and Hodges (2001) showed that the 850-hPa easterly wave at the West African coast between about 10°N and 15°N is highly correlated to TC activity in the NA. This correlation is particularly strong for the period 1994–1998. This indicates that Atlantic tropical cyclone activity is not influenced only by the total number of African easterly waves but also by the number of African easterly waves that leave the West African coast, which have significant low-level amplitudes.

The western Sahel rainfall is well correlated with ENSO events. Hence, most parts of the interannual variation in the TC activity in the NA would also be understood by an eastward shift of warm SST regions to the eastern Pacific and corresponding changes in the large-scale convection associated with ENSO (e.g., Shapiro 1987; Goldenberg and Shapiro 1996; Tang and Neelin 2004). The ENSO–TC relation results from changes in the vertical wind shear—an enhanced divergent outflow from deep cumulus convection during El Niño years results in an increase in westerly wind in the upper troposphere over the Caribbean and tropical Atlantic; however, variations in the lower tropospheric easterly winds are relatively small. Combining these different influences on zonal wind in the upper and lower troposphere, the vertical wind shear over the NA increases during El Niño years as compared to La Niña years (Gray and Sheaffer 1991); consequently, the number of TCs and their duration are reduced during El Niño (Landsea *et al.* 1999). Tang and Neelin (2004) suggested that the anomalous tropospheric temperatures arising communicated the Pacific due to wave dynamics influence the TC development by affecting column stability relative to equilibrium with NA SST. Bell and Chelliah (2006) further investigated into the tropospheric circulation and SST changes that are linked to Atlantic tropical cyclones, both on interannual and interdecadal timescales.

Larson *et al.* (2006) indicated that the AO (and/or NAO) has also acquired a strong influence on the interannual and intraseasonal variability of TC activity in the NA—an enhanced (decreased) TC activity during the positive (negative) phase of the AO. In the positive phase of the AO, the subtropical ridge in the NA is enhanced; a weakening of the Hudson Bay low in the eastern United States and a strengthening and westward extension of the Bermuda high in the western NA. The westerly wind shear is weakens over the main developing region and the tropical easterly jet intensifies over Africa. All of these characteristics provide favorable conditions for TC development. Interestingly, large-scale circulations for the positive (negative) phase of the AO appear to be similar to those for La Niña (El Niño). Namely, during La Niña years, large-scale circulation is more conducive to TC development during the AO-positive phase than during the negative phase and, during El Niño years. Therefore, it is less conducive to the TC development during the AO-negative phase than during the positive phase.

The influence of the QBO on the TC activity is known to be pronounced in the NA than in the other ocean basins (e.g., Gray 1984; Gray *et al.* 1992; Elsner *et al.* 1999). During the westerly (easterly) phase of the QBO, the strong TC genesis (i.e., hurricanes) frequency is above (below) normal. It is hypothesized that the ventilation processes in the horizontal wind across the top of the TC are a possible physical mechanism of the QBO-related change. The speed of the zonal wind in the tropical stratosphere is weak during the westerly phase of the QBO. In this case, there is relatively less ventilation resulting in a positive effect on the TC development. In addition, Shapiro (1989) demonstrated that the largest correlations between storm activity in the NA and the 30 hPa wind are observed in June. This indicates that the TCs tend to attain a higher intensity when the QBO is in its westerly phase in the tropical lower stratosphere.

Recently, however, it is noted that at least in the Atlantic, the QBO is no longer being utilized for

seasonal hurricane forecasting. The QBO–Atlantic hurricane relationship that Gray (1984) identified from 1950 to 1983 disappeared from 1984 to present date. Thus, NOAA does not consider the QBO phase for TC forecasting (Landsea, C., personal communication)

Maloney and Hartmann (2000a) suggested that the MJO is the strongest influencing factor on the intraseasonal variation of TC activity in the NA. During the westerly phase of the MJO, strong anomalous westerlies are observed in the eastern Pacific extending to the western Caribbean being altered by the southwesterlies, resulting in cyclonic circulation anomalies over the Gulf of Mexico. In this period, greatly enhanced TC activity is observed over the Gulf of Mexico and western Caribbean due to the increased genesis frequency of TC over these regions. During the easterly phase of the MJO, the TC genesis is significantly suppressed because anticyclonic circulation anomalies are formed over those regions.

c) Eastern and Central North Pacific (ECNP)

The TC activity in the ECNP is also related to the phase of ENSO and the MJO. During El Niño years, as Irwin and Davis (1999) noted, changes in the warm SST regions lead to the westward shift in the genesis location of TCs in the eastern North Pacific, thereby resulting in the propagation of TCs farther west into the central Pacific. Concurrently, there is a significant modification in the vertical shear; the decrease in the vertical shear over the tropical central North Pacific during El Niño years. The weaker vertical shear provides favorable conditions for TCs and increases the likelihood of TCs to propagate into the central North Pacific. As a result, the TC activity in the central North Pacific exceeds the normal during El Niño years and is below the normal during La Niña years (Wu and Lau 1992). For the non-El Niño years, most TCs follow a westward or northwestward track (Chu and Wang 1997; Chu 2005).

The MJO-related modulation in TC activity in the eastern North Pacific is similar to the modulation in the NA (e.g., Molinari and Vollaro 2000; Maloney and Hartmann 2000b, 2001). Over twice as many TCs are formed during the westerly periods of the MJO as compared to the easterly periods, and the TC intensity is also intensified. Therefore, the number of hurricanes during the westerly periods is over four times larger than those during the easterly periods.

d) Indian Ocean (IO)

The TC activity in the North Indian Ocean (NIO) is normally dependent upon the monsoon depression activity (Goswami *et al.* 2003). The MJO is an important modulator, which influences the clustering of the monsoon depression. During the active period of the MJO, the formation frequency of monsoon depression increases due to enhanced low-level cyclonic shear vorticity related to the westerly MJO winds. However, the evolution from the monsoon depression to TC is slightly difficult because the main developing region is adjacent to land.

Over the South Indian Ocean (SIO), during warm ENSO periods, the TC genesis was shifted westward, enhancing the TC formation west of 75°E and reducing east of 75°E. These changes in the TC genesis correspond to a westward shift of convection (Ho *et al.* 2006). This is explained by a remote effect on the SIO; the increase in SST in the central-eastern Pacific alters the Walker circulation and forms an anomalous anticyclonic circulation in the east SIO during El Niño years (Jury 1993). The spatial difference in the TC passages between El Niño and La Niña shows a significant decrease in the southeast of Madagascar but a moderate increase in the central midlatitude SIO, indicating that TCs move further east during El Niño years (Ho *et al.* 2006).

The changes in the TC activity in the SIO may be attributed to the inclusion of weak intensity systems ($v_{max} < 32 \text{ ms}^{-1}$) that are considered as TCs. It is known that ENSO increases SSTs in the warm phase in the central SIO (Lau and Nath 2003). However, destructive TCs of category 3 and higher ($v_{max} > 32 \text{ ms}^{-1}$) may be suppressed via the vertical westerly wind shear and reduced upper anticyclonic vorticity that are generated during El Niño years (Jury 1993).

The variation in the TC activity is also found to depend on various MJO phases (Bessafi and Wheeler 2006; Ho *et al.* 2006): frequent TC passages for phases 2–4 (strong convective activity straddles along the equatorial Indian Ocean) versus infrequent TC passages for additional phases. TC tracks are more south-oriented in phase 3 as compared to those in phases 2 and 4. This is possibly caused by the increased steering northerlies which are a part of the anticyclonic Gill-type Rossby wave in response to the suppressed MJO-related convection in the maritime continent.

The frequency of the TC genesis in the western SIO increases during the east phase of the QBO (Jury 1993; Jury *et al.* 1999). The Walker circulation anomaly with upper-level easterlies and lower westerlies develop in the tropics north of Madagascar in where the SSTs exceed the normal. In the subtropical region, both the trade easterlies and Hadley circulation are enhanced with a poleward shift of the midlatitude westerlies. It is noted that the QBO is in phase with ENSO approximately every 4 years with the QBO leading every 4 months. Thus, the QBO periodically exerts a similar influence on the TC activity in the western SIO.

e) Australia and the South Pacific (ASP)

The TC activity in the Australian region is higher during La Nina years and below normal average during El Nino years (e.g., Evans and Allan 1992; Nicholls *et al.* 1998; Kuleshov and de Hoedt 2003). This ENSO–TC relation is obtained from a strong correlation between the sea level pressure in Darwin, Australia, and TC days around the Australian region.

The MJO also strongly modulates the TC activity in the ASP with pronounced modulation to the northwest of Australia, i.e., there are significantly more TCs formed during the active phase of the MJO. This relationship is strengthened during El Nino periods (Hall *et al.* 2001).

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