Interannual Variability of Mean Flow Energetics over the Western North Pacific during Typhoon Season

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Abstract

The summertime SST anomalies over the Central-Eastern Pacific are closely related to the interannual variability of tropical storm (TS) occurrence over the tropical western North Pacific (WNP). Accompanying with the warm SST anomalies shift eastward in the equatorial Central-Eastern Pacific, the westerly jet, monsoon trough, anomalous upward motion and diabatic heating all extend southeastward. The large-scale circulations modulated by summertime ENSO provide a favorable environment for TS occurrence. The maintenance of these large-scale anomalous circulations is investigated by the mean flow energetics in this study.

During the SST warm period, both the mean available potential energy (MAPE) and mean kinetic energy (MKE) increase over the WNP. The increment of MAPE in the tropics is mainly contributed by the generation of MAPE associated with the heightened diabatic heating over warm region. As the upward motion intensified, the MAPE converts to MKE to maintain the anomalous large-scale circulations. The enhancement of these anomalous circulations plays an important role for transient eddies growth because it provides a suitable condition for eddy baroclinic and barotropic energy conversions.

1. Introduction

The El Nino-Southern Oscillation (ENSO) is a pronounced mode of interannual variability in the air-sea coupling system. The dynamic and thermodynamic conditions of tropical atmosphere and ocean are modulated by local or remote ENSO forcing, then influence the worldwide climate and weather phenomena. The interannual variations of tropical storm (TS) activity over the western North Pacific (WNP) are linked to the anomalous large-scale circulations associated with ENSO. Accompanying with the strengthened and eastward stretching of monsoon trough and westerly jet along 5°-15°N, the formation regions of TS over the WNP also extends southeastward during the warm ENSO period. The modulations of dynamical fields associated with ENSO provide a suitable environment for TS development (Chen et al. 1998, Wang and Chan 2002, Tsou et al. 2006). On the other hand, the thermodynamic processes of diabatic heating can build up the available potential energy (Lorenz 1955) to energize the atmosphere and then force the large-scale circulation in the tropics. Examining the processes of the atmospheric energy cycle is a vital way to understand the large-scale atmospheric dynamics (Kung 1966), as well as the growth and decay of synoptic-scale disturbances (e.g. Norquist et al. 1977; Lau and Lau 1992). However, few researches investigated the interannual variations of mean flow energy and the differences of energy transforms between SST warm and cold years. The main purpose of this study is to understand the physical processes maintaining the large-scale circulations which might be beneficial for the TS activity during ENSO year from the atmospheric energetics viewpoint.

2. Data and Interannual Classifications

The National Centers for Environmental Prediction (NCEP) / National Center for Atmospheric Research (NCAR) reanalysis data (Kalnay et al. 1996) of u, v, ω, T and geopotential from 1979 to 1998 are used to examine circulation and energetic analysis. The monthly Sea Surface Temperature (SST) for the period 1979 to 1998 obtained from the NCEP/NCAR (Reynolds and Smith 1994) is also adopted in this study. The interannual classifications are stratified by the July-September SSTA in Nino3.4 region: warm years (SSTA ≧ 0.8 standard deviation), cold years (SSTA ≦ -0.8 standard deviation) and normal years (-0.8 standard deviation < SSTA < 0.8 standard deviation). Table 1 shows the results of stratifications.

Table 1 Stratification of 3 categories based on the standard deviations of July-September seasonal mean SSTA in Nino3.4 region.

Warm years (SSTA > 0.8 S.D.)	1982, 1987, 1991, 1997
Normal years (-0.8 ≦ SSTA ≦ 0.8 S.D.)	1979, 1980, 1983, 1984, 1986, 1989, 1990, 1992, 1993, 1994, 1995, 1996
Cold years (SSTA < -0.8 S.D.)	1981, 1985, 1988, 1998

3. Energy budget equation

Similar with Lorenz (1955), the available potential energy in our study may also be expressed in terms of two components, a time mean flow and an eddy component. The expression for time mean and eddy available potential energies are

$$\overline{A} = \frac{1}{2}\int_0^{\infty}(\Gamma_d - \Gamma)^{-1}\frac{\overline{T^{*2}}}{\tilde{\overline{T}}}dp \qquad (1)$$

$$A' = \frac{1}{2}\int_0^{\infty}(\Gamma_d - \Gamma)^{-1}\frac{(T^{*\prime})^2}{\tilde{\overline{T}}}dp \qquad (2)$$

where the symbol "$\sim$" represents sphere surface average, the asterisk signifies departure from sphere surface average, the symbol "$\overline{\ \ }$" represents seasonal mean, while " $'$ " is the deviation from time mean. $\Gamma_d = g/C_p$ is the dry-adiabatic lapse rate and $\Gamma = -\partial T/\partial z$ is the observed lapse rate of temperature.

Attempt to diagnostic the energy sources of mean flows, the budget equations of mean available potential energy (MAPE) and mean kinetic energy (MKE, $\overline{K} = \frac{1}{2}(\overline{u}^2 + \overline{v}^2)$) were derived as equation (3) and (4), respectively.

$$\frac{\partial \overline{A}}{\partial t} = -C_M - C_A + G_M \qquad (3)$$

$$\frac{\partial \overline{K}}{\partial t} = C_M - C_K - D_M$$

where t is time, $-C_M$ and C_M are conversion of MKE to MAPE, $-C_A$ the conversion of EAPE to MAPE, G_M is the generation of MAPE, $-C_K$ the barotropic energy conversion from EKE to MKE, D is the dissipation term. Those energy conversion and source/sink terms were calculated with seasonal mean from July to September and expressed as follow:

$$\overline{C_M} = -\frac{R}{p}\overline{T^*}\,\overline{\omega} \qquad (5)$$

$$\overline{C_A} = \frac{C_p}{\tilde{\overline{T}}}\frac{\Gamma_d}{\Gamma_d - \Gamma}\overline{T^{*\prime}V_3'}\cdot\nabla_3\overline{T^*} \qquad (6)$$

$$\overline{G_M} = -\frac{\Gamma_d}{\Gamma_d - \Gamma}\frac{\overline{T^*}\,\overline{Q}}{\tilde{\overline{T}}} \qquad (7)$$

$$\overline{C_K} = \overline{V'(V_3\cdot\nabla_3)\overline{V}} \qquad (8)$$

Further definitions in (5)-(8) are p the pressure, R the gas constant, ω the vertical velocity, T the temperature, C_p the specific heat at constant pressure, Q is the diabatic heating. The suffix 3 presents the three-dimension vector

4. Results

Fig. 1 shows the distributions of difference of SST, circulations and TS frequencies between warm and cold years over the WNP. To the northwest of warm SST, a low-level anomalous cyclonic circulation is coupled with an anomalous anticyclone in high-level (Fig. 1 a. and 1 b.). The atmospheric responses associated with the warm SST anomalies in the equatorial central Pacific consist considerably with the Rossby wave pattern forced by diabatic heating only (Gill 1980). However, the atmosphere shows an asymmetric response that the maximum center of low-level anomalous cyclone is located to the north of the high-level anomalous anticyclone. To the south of anomalous cyclone (anticyclone) in low (high) level, there is a strong westerly (easterly) anomaly along 5°-15°N in the Central-Western Pacific. These large-scale circulation anomalies over the WNP create a favorable environment for tropical storms generation and development. The frequencies of tropical storms increase significantly in a southeast-northwest oriented band extending from dateline to the southeast of Taiwan where are consisted with low-level westerly and cyclonic regions (Fig. 1 c.).

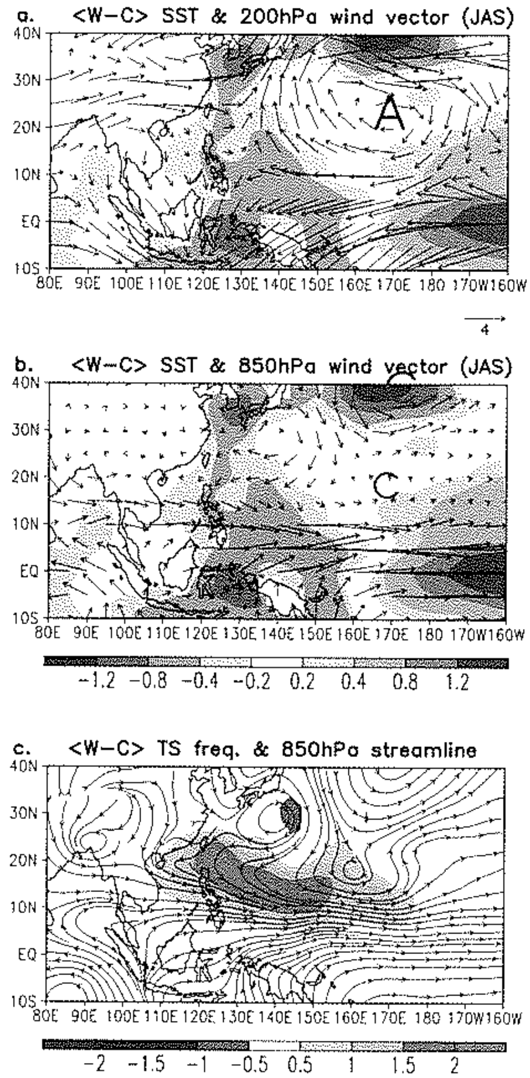

Fig1. Warm minus cold years (a) SST and 200hPa wind field, (b) SST and 200hPa wind field and (c) TS frequency and 850hPa streamline. The shaded in (a) and (b) represents SST, Unit:℃. The symbols A and C indicate the anticyclonic and cyclonic circulation, separately.

During the SST warm period, both the mean available potential energy (MAPE) and mean kinetic energy (MKE) increase over the WNP (not shown). The increment of MAPE in the tropics is mainly contributed by the generation of MAPE associated with the heightened diabatic heating over warm region (Fig. 2 a.). The difference of MAPE generation between warm and cold years shows a wavetrain pattern that the positive anomalies are along 5°-15°N, while the negative anomalies MAPE generations are located on the northern and southern sides of positive anomalous region. In addition, as the upward motion intensified, the MAPE converts to MKE to maintain the anomalous large-scale circulations (Fig. 2 b.). The distribution of the energy conversion from MAPE to MKE is similar with the generation of MAPE (compared with Fig. 2 a.and b.).

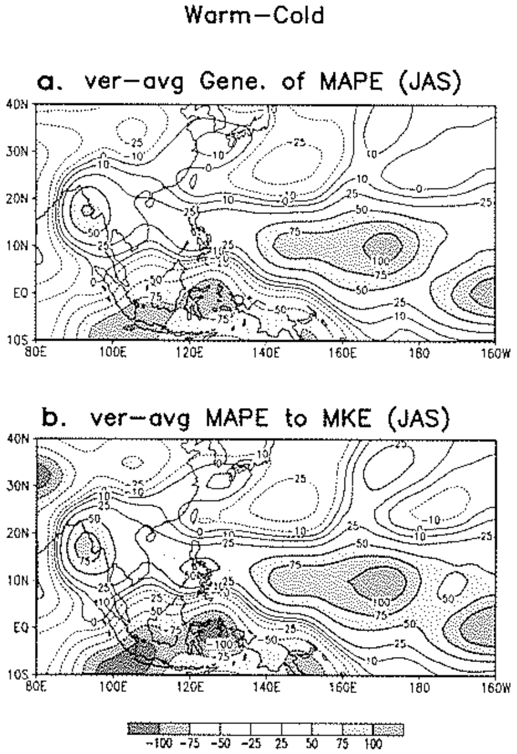

Fig2. Warm minus cold years of vertically averaged distributions of (a) generation of MAPE and (b) the energy conversion from MAPE to MKE. Unit: $10^{-5}m^2s^{-3}$.

It is suggested that the loss of MAPE through the mean flow baroclinic energy conversion is furnished by the generation of MAPE associated with diabatic heating. During warm years, the strong energy conversion from MAPE to MKE extends eastward along 5°-15°N that may maintain the enhanced low-level (high-level) westerly (easterly) (Fig 1 a. and b.). The enhanced low-level westerly during warm years provides a favorable environment for barotropic energy conversion from MKE to EKE that contributes the transient eddies, like TS, growth doring warm years (not shown). This result is similar with Maloney and Hartmann (2001) who indicate that the barotropic energy conversions would provide more EKE for perturbations growth during westerly winds regimes.

Because the temperature gradients in the tropics are very small, the energy conversions from MAPE to EAPE through the temperature advections associated with eddy transports is relative small (Fig 3 a.). The positive anomalous energy conversion from MAPE to EAPE is about one to two orders of magnitude small than the mean baroclinic energy conversions (MAPE to MKE). The enhanced EPAE generations during warm years are over the WNP with a similar magnitude of MAPE to EAPE energy conversion (Fig 3 b.). The two terms have positive anomalies over the WNP where the TSs have higher occurrence (Fig. 3 a. and b.). It is suggested the growth of EAPE due to the enhanced MAPE to EAPE conversion and the generation of EAPE during warm years both account for the increased eddy baroclinic energy conversions from EAPE to EKE that might be beneficial for TS occurrence (Fig 3 c.).

5. Summary

The summertime SST anomalies over the Central-Eastern Pacific are closely related to the interannual variability of tropical storm (TS) occurrence over the tropical western North Pacific (WNP). Accompanying with the warm SST anomalies shift eastward in the equatorial Central-Eastern Pacific, the westerly jet, monsoon trough, anomalous upward motion and diabatic heating all extend southeastward.

The interannual variations of energy conversion cycle for sustaining the mean flow and eddies are shown in Fig. 4. During the SST warm period, the increment of MAPE in the tropics is mainly contributed by the generation of MAPE associated with the heightened diabatic heating over warm region. As the upward motion intensified, the MAPE converts to MKE to maintain the anomalous large-scale circulations which provide a favorable environment for TS occurrence. The large-scale circulation not only favors the TS activities directly, but also provides a suitable condition for eddy barotropic energy conversions. At the same time, the EKE growth transformed by MKE. On the other hand, the generation of EAPE is also enhanced during warm years, and then converts to EKE. Both the eddy barotropic and baroclinic energy conversions provide a favorable condition for the growth of transient eddies including tropical storms during summertime ENSO periods.

Warm–Cold

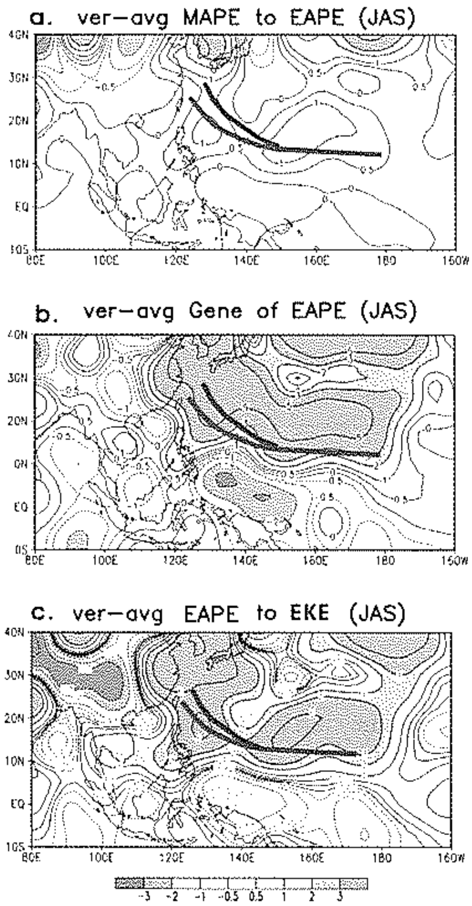

Fig 3. Warm minus cold years of vertically averaged distributions of (a) the energy conversion from MAPE to EAPE, (b) the generation of EAPE and (c) eddy baroclinic energy conversions. Unit: $10^{-5}m^2s^{-3}$. The tropical storm tracks are superimposed on each figure.

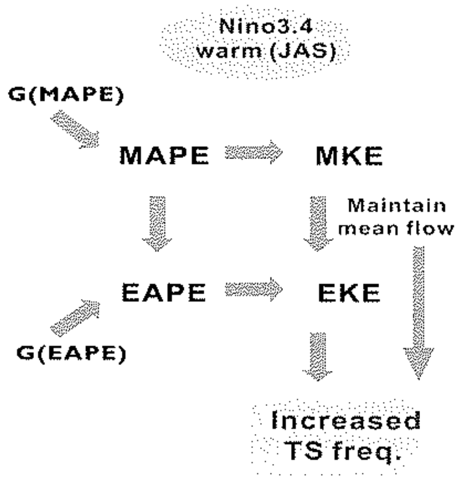

Fig 4. The energy conversion diagrams during summertime ENSO period.

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