Influence of ENSO Event on the Maintenance of Pacific Storm Track in the Northern Winter

Zhu Weijun (朱伟军) and Sun Zhaobo (孙照渤)①

Nanjing Institute of Meteorology, Nanjing 210044

(Received August 21, 1998; revised November 6, 1998)

ABSTRACT

An influence of ENSO event on the maintenance of Pacific storm track in the Northern winter is studied based on the NCEP / NCAR daily re-analysis data. The result shows that in El Niño (La Niña) year an increase (decrease) of baroclinicity over the storm track, extension (withdrawal) eastward and southward (westward but northward for its east end) of its position and augmentation (debilitation) of its strength are closely in response to the enhancement (abatement) of eddy heat flux and momentum flux that are associated with the development of the storm track. It thus indicates that ENSO event exerts an important impact on its maintenance and development in the Pacific Ocean.

Key words: ENSO, Storm track, Baroclinicity

1. Introduction

It is well known that there is an obvious interaction between circulations in– and extra–tropics, which usually exhibits a unique feature during ENSO period (Bjerknes, 1969; Huang, 1991; Hoskins and Karoly, 1981; Horel and Wallace, 1981: among others). The research reveals that an eddy flux caused by a transient disturbance in the middle latitude during the period of ENSO event plays an important role in the maintenance of anomalous atmospheric circulation pattern, triggered by sea surface temperature anomaly at equator, in the Pacific Ocean and the North America. Its distribution itself is also affected by SSTA in the equatorial Pacific (e. g., Held et al., 1989; Hoerling and Ting, 1994; Straus and Shukla, 1997). A storm track is usually referred to as a region where a transient disturbance is extremely violent during the period of 2.5–6 days. There are two most remarkable storm tracks located in the two oceans in the middle latitude of the Northern Hemisphere. Condensation heating anomaly resulted from transient disturbances over storm tracks not only generates a substantial influence on global circulation but also brings about weather and climate changes. In view of this fact, making a study on the anomalous physical mechanism with which a storm track can be maintained and developed is of great significance to weather forecasting and short–range climate prediction. Many meteorologists both at home and abroad since 1980 (e.g., Blackmon et al., 1977; Lau, 1978; Deng and Sun, 1994) have made a thorough study in terms of three–dimensional structure, temporal variation and energy transformation of storm tracks. As a result, many features have been discovered. Although a lot of achievements have been scored in research on the maintenance and dynamic mechanism in the recent years (e. g., Hoskins and Valdes, 1990; Cai and Mak, 1990; Chang and Orlanski, 1993; Zhu and Sun, 1995), there still have many problems that need to be further studied in

①Sponsored by the National Natural Science Foundation of China, under grant number of 49635180.

this perspective, including the impact of an external tropical heat resource forcing on the maintenance of a storm track. For this reason, the focus in this paper, proceeded from the effect of the eastern equatorial Pacific SSTA on the Pacific storm track at the time when ENSO happens, is put on the study on the maintainable mechanism of the storm track on the basis of observational data.

2. Data and methods

Based on the re-analyzed data from NCEP / NCAR, the years 1982 / 83 (November, December and January, hereafter NDJ), 1986 / 87 (NDJ) and 1991 / 92 (NDJ) were selected as three representative winters of El Niño year; while, the years 1984 / 85 (NDJ) and 1988 / 89 (NDJ) were chosen as two representative winters of La Niña year. Transient eddies with a duration of 2.5–6 days can be filtered out from the data by means of a 31–point digital filtering method developed by Sun et al. (1992). These transient quantities are then used to calculate over the Northern Hemisphere the synoptic geopotential height variance ($\overline{Z'^2}$) and disturbance energy ($E_K = \frac{1}{2}\overline{(u'^2 + v'^2)}$) at 500 hPa, meridional transfer of westerly momentum ($\overline{u'v'}$) at 300 hPa, and horizontal and vertical heat transfer ($\overline{v'T'}$, $\overline{\omega'T'}$) at 850 hPa in order to discuss in details the process and mechanism with which ENSO has an influence over the Pacific storm track in the Northern winter.

The maximum growth rate of Eady wave is introduced in line with Hoskins and Valdes (1990):

$$\sigma_{BI} = 0.31 f \left|\frac{\partial \overline{V}}{\partial Z}\right| N^{-1} .$$

Where the symbols in the right hand side are common meteorological marks. Regardless of the influence exerted by horizontal wind shear and moist process in the low layer of air stream, the quantity can yet be regarded as a very good criterion used to measure the strength of the baroclinicity in middle latitudes.

In addition, according to Hoskins et al. (1983) and Edmon et al. (1980), vectors $\vec{E} = (\overline{v'^2 - u'^2}, -\overline{v'u'})$ and $\vec{F} = (-r_0\cos\varphi\overline{v'u'}, f r_0\cos\varphi\overline{v'\theta'}/\theta_p)$ (in XOY and YOP planes, respectively; known combined as extended Eliassen–Palm flux vector) and their divergence would be introduced to express the interaction between the time–mean flow and transient eddies.

Finally, a t–test is applied to viewing the statistical significance for the difference of some mean variance or covariance fields in two independent samples (i.e., El Niño & La Niña). According to Snedecor et al. (1990), first calculating

$$t = \frac{(\overline{X}_P - \overline{X}_N)}{\sqrt{S_P^2 / n_P^2 + S_N^2 / n_N^2}} \quad \text{at each grid points} ,$$

where $\overline{X}_P$, $\overline{X}_N$: the mean of samples; S_P^2, S_N^2 : the unbiased estimate of each sample variance; $n_P = 3$, $n_N = 2$: the sample size,then calculating freedom:

$$df = (S_p^2 / n_p + S_N^2 / n_N)^2 / d$$

$$d = [\left(\frac{S_P^2}{n_P}\right)^2 / (n_P - 1) + \left(\frac{S_N^2}{n_N}\right)^2 / (n_N - 1)] .$$

In the end we will compare t and t_α (at α level with freedom df). if $|t| > t_\alpha$, we will otherwise refuse the assumption that there is no difference in this two–sample mean. In the paper, the critical value $t_\alpha = 2.35$ (at $\alpha = 0.05$ level with mean freedom 3).

3. Result analysis

3.1 *Variations of position and strength of pacific storm track*

In general, a storm track is defined as an area where there is severe synoptic–scale eddy with a duration of 2.5–6 days. It is closely associated with the paths of cyclones and anticyclones on daily ground weather map. The position and strength in a given time can be described by a variance or covariance field of time filtering data. In this paper, a field of 500 hPa mean synoptic geopotential height variance is used to discuss the variation of position and strength of winter Pacific storm track. It can be seen from a climate–mean figure (omitted) that the maximum values of synoptic geopotential height variance are extendedly distributed in the Pacific Ocean of the whole middle latitudes between 30–50°N with an extreme value center located in about 42°N in the vicinity of the central Pacific, which is just the mean position and strength of the Pacific storm track in winter; while in the historical figure over the years (omitted) it is manifested that the storm track possesses a characteristic of quite strong interannual variation in both its intensity and position, the latter often fluctuates in south–north and east–west directions. Fig. 1 depicts 500 hPa synoptic geopotential height variance. It can be seen that there is only a maximum center around 50 dagpm^2 in the Pacific storm track for El Niño year (Fig. 1a), as composed to two such centers appearing there for La Niña year (Fig. 1b), with one of which (~35 dagpm^2) lying in the Ocean to the east of the Aleutian Islands while the other (~45 dagpm^2) in the climatological position. Therefore, over the storm track at the east end of the central and eastern Pacific Ocean between 30–40°N the synoptic–scale geopotential height variance in El Niño year increases more remarkably than that in La Niña year (Fig. 1c). The shaded area in Fig. 1c denotes significance at and in excess of $\alpha = 0.05$ level. This characteristic is also similarly performed in the diagram of 500 hPa mean synoptic disturbance kinetic energy (not shown). It is thus easy to see that in El Niño year the position of the winter Pacific storm track extends eastward and southward substantially and its intensity also increases remarkably; while, it splits into two centers and the intensity becomes weak in La Niña year, with its west end contracting westward a little bit compared to the northward shift for its east end.

3.2 *Variation of baroclinicity over Pacific storm track*

Fig. 2 shows an distribution of mean baroclinic strength index in 775 hPa. Lau (1978) indicates that there does exist a significant difference in the structure between two ends of the storm track, that is, the west end seems to be in a baroclinic state, while the east one gradually varies into a quasi–barotropic state, which are well manifested in Figs. 2a,b. The baroclinicity over the Pacific storm track in El Niño year (Fig. 2a) is relatively strong with a maximum at the extreme value center reaching as long as over 1.2 day^{-1} and the isoline of 0.8 day^{-1} extends all the way to the east to across the date line until around 165°W. In contrast, the

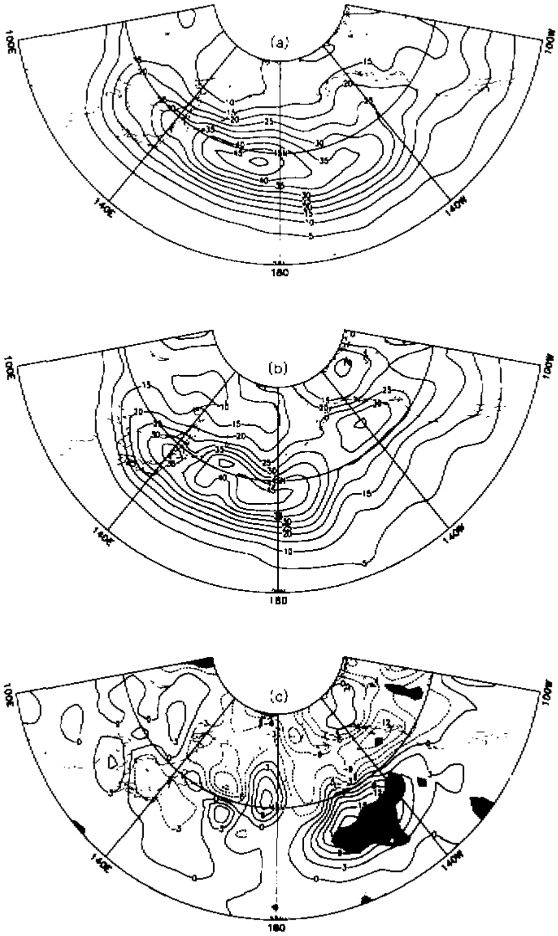

Fig. 1. 500 hPa synoptic geopotential height variance for El Niño (a) and La Niña (b) years and their difference (c) with contour interval of 5.0 (a, b) and 3.0 (c) dagpm^2, respectively.

baroclinicity in La Niña year (Fig. 2b) is quite weak. Although the maximum strength at the extreme value center is equivalent to 1.0 day^{-1}, the eastern boundary of the 0.8 day^{-1} isoline only hardly reaches the date line. This characteristic can be seen even more clearly in its contrast figure (Fig. 2c) in which the baroclinicity in the whole region of a storm track in El Niño year is much stronger than that in La Niña year. It is worth noting that the baroclinic strength increased at the east end of the storm track in the central and eastern Pacific where the baroclinicity is quite weak for the mean. And this area again is significant at $\alpha = 0.05$ level (shaded in Fig. 2c).

Activities of synoptic eddies over storm tracks in the Northern Hemisphere can be expressed by the life cycle of a developing baroclinic wave (Simmons and Hoskins, 1978). The increase (decrease) of the baroclinicity, therefore, plays a key role in the maintenance and development of a storm track. Comparison between Figs. 1 and 2 shows that the maxima in baroclinicity is not necessary in full agreement with the counterpart of synoptic eddies in the

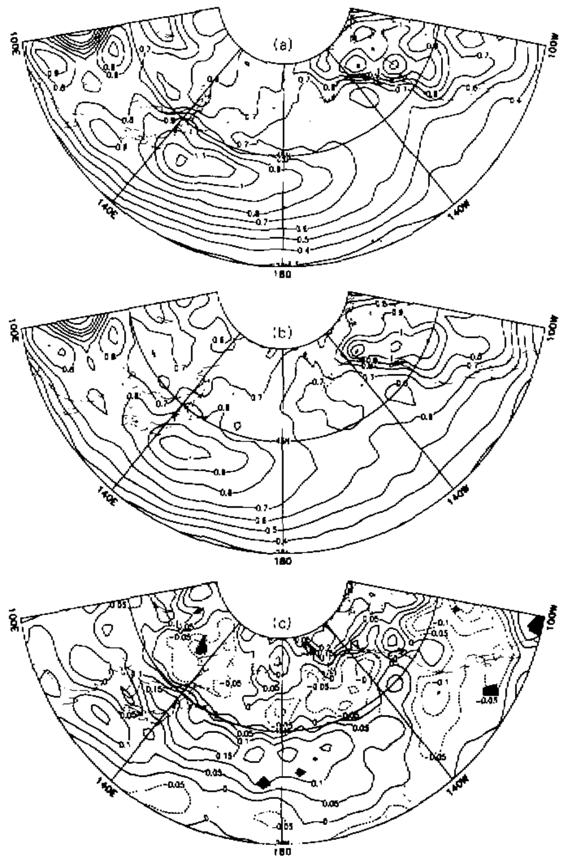

Fig. 2. 775 hPa mean distribution of baroclinicity for El Niño (a), La Niña (b) years and their difference (c) with contour interval of 0.1 day^{-1} for (a) and (b) and 0.05 day^{-1} for (c), respectively.

storm track, with the latter lying more often in the northward and downstream of the former. As such, the increased baroclinicity in Fig. 2c bears a responsibility for the activities of synoptic–scale eddies over the east part of the storm track, which therefore explains partly why the storm track can be maintained in a quite weak baroclinic region.

The cause of the increasing of the baroclinic strength can be interpreted by the fact that when El Niño event happens the warm SSTA in the eastern equatorial Pacific may result in an augmentation of mean temperature gradient on both sides of its north and south over the storm track, which in turn increases available potential energy that is conducive to the strengthening of baroclinicity in the region; while it is just opposite when La Niña event appears.

3.3 *Variation of synoptic eddy heat flux and westerly momentum flux over Pacific storm track*

Figs. 3a and 3b exhibit distributions of the difference in meridional $\overline{v'T'}$ and vertical flux $\overline{\omega'T'}$ of 850 hPa mean synoptic eddy heat, respectively. They show that in the central and

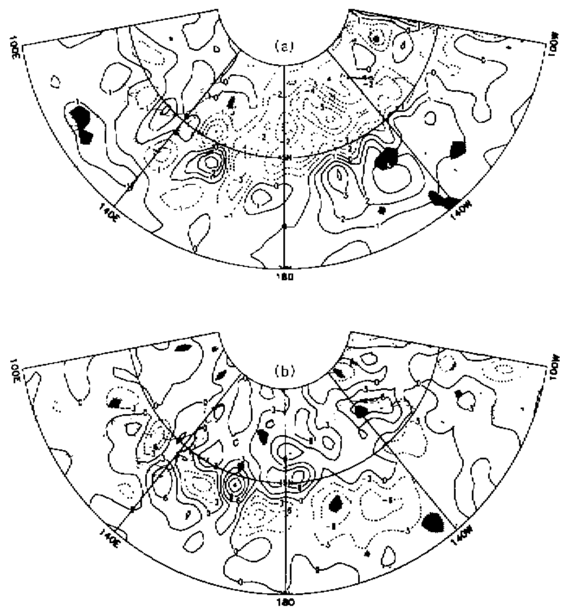

Fig. 3. Difference (El Niño–La Niña) in 850 hPa synoptic meridional (a) and vertical (b) eddy heat flux with contour interval of 1.0 km / s and 3.0×10^{-2} kPa / s.

eastern Pacific between 30–40°N the $\overline{v'T'}$ is positive and $\overline{\omega'T'}$ is negative, and both are significant at $\alpha = 0.05$ level (shaded area). This explains that the poleward and upward flux transportation of synoptic eddy heat is strengthened at the east end of the storm track in El Niño year compared with that in La Niña year. Its position is comparatively in conformity to the place where the synoptic geopotential height variance and disturbance kinetic energy discussed in the last section are increased. As the severe poleward and upward transportation of synoptic eddy heat flux is one of the most important features in the phase of substantial development of baroclinic wave, it can be concluded that in El Niño year the storm track will be intensified at its east end due to the warm SSTA in the central and eastern equatorial Pacific.

Fig. 4a shows a difference in 300 hPa synoptic westerly momentum meridional flux $\overline{u'v'}$, from which it can be seen that compared with La Niña year the convergence of meridional synoptic westerly momentum flux in the central and eastern Pacific at about 40°N is enhanced in El Niño year at $\alpha = 0.05$ significance level (shaded area). This position is primarily conformed with the place where the meridional flux of climate–mean synoptic westerly momentum is converged. Due to the convergence of meridional flux associated with eddy voticity transportation, it is of great significance to the maintenance of the intensity of mean westerly jet. The convergence intensified at the east end of the Pacific storm track is therefore conducive to the maintenance of westerly jet in that region.

3.4 *Variation of interaction between time–mean flow and synoptic eddies over Pacific storm track*

The three–dimensional extended E–P vector is one of the important diagnostic tools

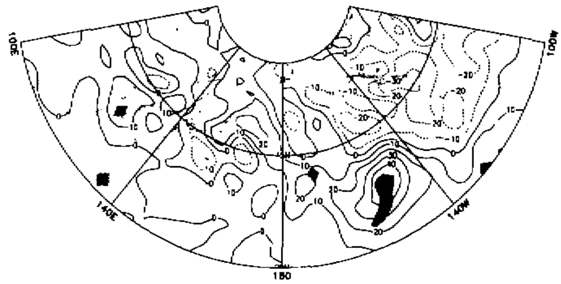

Fig. 4. Difference (El Niño–La Niña) in 300 hPa synoptic meridional flux of westerly momentum with contour interval of 10.0 m^2 s^{-2}.

commonly used in the study of the mean–flow interaction. While its horizontal components describe the characteristic anisotropy of horizontal eddy shape and the meridional transport of westerly momentum flux, its vertical component gives a measure of the vertical transport of eddy heat flux. The direction of the vector is in some way related to the group velocity of the eddy energy dispersion. And its divergence reflects the mechanical forcing of transient eddies on the time–mean flow. Firstly, as can be seen from its XOY–components (Figs. 5a,b) that the vector $\vec{E}$ is west–east oriented all over the northern mid–latitudes, implying the synoptic eddies there have longer meridional scale as composed to the zonal counterpart. Moreover, it is also shown that the vector $\vec{E}$ shows north–east (south–east) directed to the north (south) of 45°N, therefore the divergence of the vector is also lying along this latitude. This $\vec{E}$–revealed distribution of the synoptic transient eddies, in effect, reflects the actual tracks of moving cyclones and anticyclones. Generally speaking, the northern mid–latitude cyclones are shifting from west to east, then north–east into the Aleutian low compared to the finally south–east merging into the sub–tropical high for the anticyclones. It is obvious, comparatively, that the vector $\vec{E}$ and its divergence over the Pacific storm track during the northern winter extend further to the east and south in El Niño year than that in La Niño year, which is in good agreement to the eastward extension of the storm track concluded in Section 3.1. Secondly, the YOP–components $\vec{F}$ will be taken into consideration. Fig. 6 gives the regional average of $\vec{F}$ and its divergence over the Pacific area (150°E–150°W). We can see from it that the maximum upward eddy heat flux in El Niño year lies further south than that in La Niña year, which is in close association to the enhancement of synoptic eddy activity over the central and east part of the Pacific storm track. It is also shown that the upper level divergence of vector $\vec{F}$ between 35–45°N exists significant increase in El Niño year compared to that in La Niña year.

In view of the fact that the divergence of $\vec{E}$ and $\vec{F}$ is relative to the acceleration of westerly, it is therefore concluded that at equator in El Niño winter the warm SSTA in the central and eastern Pacific enhances the interaction between synoptic transient eddy and mean–time flow in the Pacific storm track region, especially in its east end, and the mechanical forcing of the transient eddy has a function to maintain the mean westerly jet strength there (Fig. 5d).

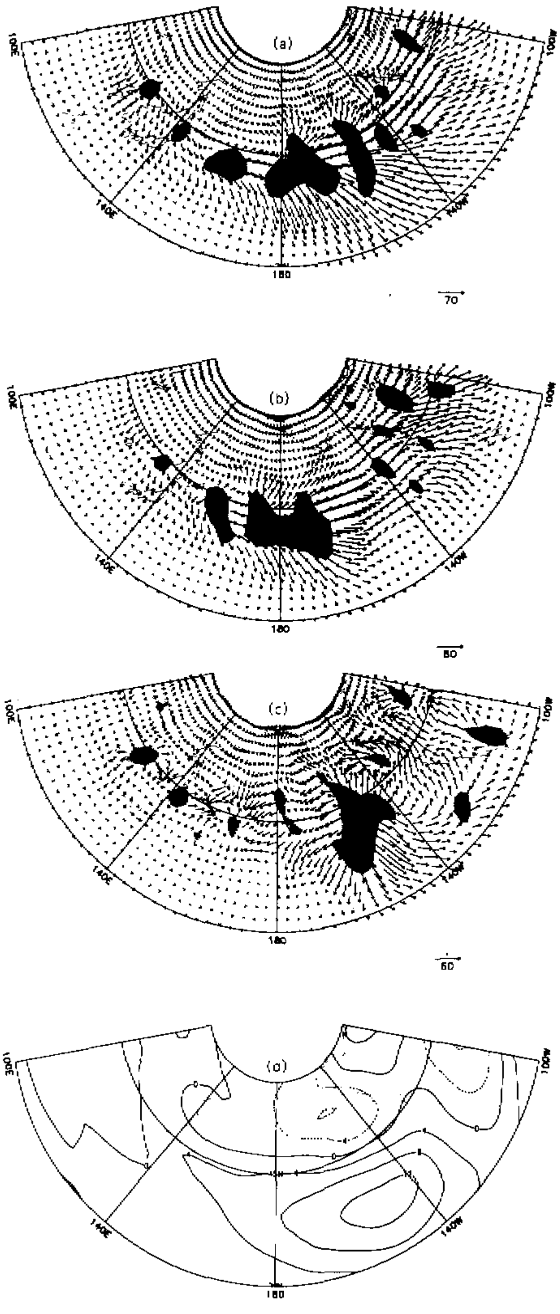

Fig. 5. 300 hPa $\vec{E}$ vector and its divergence for El Niño (a), La Niña (b) years and their difference (c) with standard vector length (m^2 s^{-2}) shown at bottom right (shaded indicates divergence $\geq$ (4.0 $\times 10^{-5}$ m s^{-2}). (d) is the difference in 300 hPa zonal wind with contour interval of 5.0 m / s.

It is common knowledge that the position of the storm track is well in correspondence with the jet in the upper troposphere. The former is usually located on poleward side and in downstream of the latter, and their intensities possess an identical trend of changes (Deng and Sun, 1994). Consequently, ENSO event can produce an influence on jet, which in turn has an impact on storm tracks. The process of this effect is possible. As Hoerling and Ting (1994) and Wu et al. (1986) indicate that any simple heat resource situated in the central and eastern equatorial Pacific is strong enough to compel a formation of tropical anticyclone whose position is located in a little bit east to the climate mean West Pacific high pressure, it will give rise to the eastward and southward extension of the subtropical jet and the Pacific storm track as well. From Fig. 5d we can see that the mid–latitude westerly during the Northern winter in deed extends further eastward and southward in El Niño year as composed to that in La Niña year. Such variation of the jet, however, includes the positive contribution by synoptic eddy forcing as mentioned above. As such, the interaction between transient waves of synoptic–scale and mean flow still needs to be further studied.

3.5 *Comprehensive analysis*

Briefly, the concrete process of the effect of ENSO event on the maintenance of Pacific

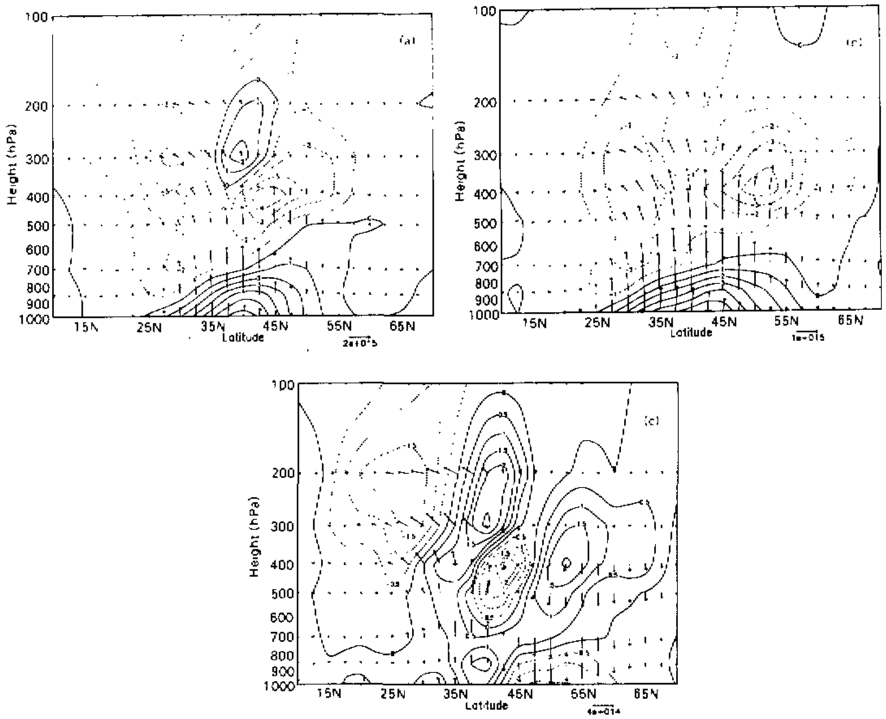

Fig. 6. Eliassen Palm cross–section for El Niño (a), La Niña (b) years and their difference (c) with standard vector length shown at bottom right (note the y– and P–components are multiplied by $2\pi a\cos\varphi / g$ and $2\pi a^2\cos\varphi / g$ and in units of m^3 and m^3 kPa, respectively). The isolines (every 1.0×10^{15} m^3 for (a), (b) but 0.5×10^{15} m^3 for (c)) are for the E–P flux divergence.

storm track in the Northern winter can be summed up as follows:

ENSO (La Niña) year→warm (cold) SSTA in the central and eastern equatorial Pacific →increasing (decreasing) of baroclinicity in the middle section and at the east end of the storm track→ synoptic–scale disturbance strengthening (weakening) and eastward and southward extension (westward debilitation, but another center appearing to the north–east) →significance (insignificance) of poleward and upward transportation of eddy heat flux → maintenance of the storm track in the middle section and at the east end. It can be then concluded that SSTA in the central and eastern equatorial Pacific, as an external heat resource forcing in the low latitudes, plays an extremely important role in the east–west displacement of the storm track in the winter Pacific and its maintenance in a weak baroclinic region.

4. Conclusion and discussion

1. The position of the storm track in the winter Pacific Ocean extends eastward and southward very distinctly and its intensity increases substantially in El Niño year; while in La Niña year it splits into two centers, with the main one contracting westward a little bit and the east one lying northward, and the intensity seems to be quite weak. Therefore, ENSO event plays an important role in the west–east shift of the storm track in the Northern winter.

2. In response to the point (1), the poleward and upward flux transportation of synoptic eddy heat in El Niño year is relatively strong; while it is quite weak in La Niña year. According to the theory of baroclinic wave, the baroclinic variation over the storm track, aroused by SSTA in the central and eastern equatorial Pacific, is an important reason for the effect of ENSO event on the maintenance of the Pacific storm track in the Northern winter.

3. Compared with the convergence of meridional flux of synoptic westerly momentum in the upper troposphere and the divergence of E–P flux in La Niña year, those in El Niño year increase very significantly in the vicinity of 40°N in the central and eastern Pacific Ocean, which explains that the mechanical forcing of transient eddy has functions to maintain the mean–time jet strength there. It thus may serve as a link in the process of ENSO event's impact on storm tracks.

REFERENCES

Bjerknes, J., 1969: Atmospheric teleconnections from the equatorial Pacific. *Mon. Wea. Rev.*, **97**, 162–172.

Blackmon, M. L., J. M. Wallace, N–C. Lau, et al., 1977: An observation study of the Northern Hemisphere wintertime circulation. *J. Atmos. Sci.*, **34(7)**, 1040–1053.

Cai, M., and M. Mak, 1990: On the dynamics of regional cyclogenesis. *ibid.*, **47(12)**, 1417–1442.

Chang, E. K. M., and I. Orlanski, 1993: On the dynamics of a storm track. *ibid.*, **50(7)**, 999–1015.

Deng Xinxou, Sun Zhaobo, 1994: Characteristics of stormtrack's variation with time in the Northern Hemisphere. *Journal of Nanjing Institute of Meteorology*, **17(2)**, 165–170 (in Chinese).

Edmon H. J., B. J. Hoskins, M. E. McIntyre, 1980: Eliassen–Palm cross sections for the troposphere. *J. Amos. Sci.*, **37(12)**, 2600–2616.

Held, I. M., S. W. Lyons, and S. Nigam, 1989: Transients and the extratropical response to El Niño. *J. Atmos. Sci.*, **46(1)**, 163–174.

Hoerling, M. P., and M. Ting, 1994: Organization of extratropical transient during El Niño. *J. Climate*, **7**, 745–766.

Horel, J. D., and J. M. Wallace, 1981: Planetary scale atmospheric phenomena associated with the Southern Oscillation. *Mon. Wea. Rev.*, **109**, 813–829.

Hoskins, B. J., and D. J. Karoly, 1981: The steady linear response of a spherical atmosphere to thermal and orographic forcing. *J. Atmos. Sci.*, **38**, 1179–1196.

——, I. N. James, G. H. White, 1983: The shape propagation and mean–flow interaction of large scale weather system. *ibid.*, **40(7)**, 1595–1612.

——, P. J. Valdes, 1990: On the existence of stormtracks. *ibid.*, **47(15)**, 1854–1864.

Huang Yonghui, 1991: *Teleconnection of the atmospheric circulation, Modern Climate Research*, China Meteorological Press, 113–136 (in Chinese).

Lau, N–C., 1978: On the three–dimensional structure of the observed transient eddy statistics of the Northern Hemisphere wintertime circulation. *J. Atmos. Sci.*, **35(10)**, 1900–1923.

Simmons, A. J., B. J. Hoskins, 1978: The life circle of some nonlinear baroclinic waves. *ibid.*, **35(3)**, 432–441.

Snedecor, G. W., W. G. Cochran, 1991: *Statistical Method*, Translated by Liu Chuiyu et al., Shanghai Translation Press 109–139.

Straus, D. M., and J. Shukla, 1997: Variations of midlatitude transient dynamics associated with ENSO. *J. Atmos. Sci.*, **54(7)**, 777–790.

Sun Zhaobo, 1992: Statistical characteristics of 40–60–day oscillation in the atmosphere of extratropical region. *Selection of Long–range Weather Forecasting*, edited by Zhang Jijia, China Ocean Press, 29–35 (in Chinese).

Wu Guoxong, U. Cubasch, 1986: The influence of El Niño SSTA on the zonal–mean meridional circulation and atmospheric transportation feature. *China Science* (Volume B), **10**, 1109–1120 (in Chinese).

Zhu Weijun, Sun Zhaobo, 1995: Numerical study on the effect of SSTA in the Northwest Pacific on storm tracks in winter Pacific. *Journal of Nanjing Institute of Meteorology*, **18(4)**, 478–485 (in Chinese).