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# NON-LINEAR CRITICAL LAYER IN EL NIÑO AND LA NIÑA YEARS AND FORMATION, MAINTENANCE AND OSCILLATION OF THE SUBTROPICAL HIGH*

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**ABSTRACT:** Monthly mean zonal wind data from the European Center for Medium-range Weather Forecasting (ECMWF) for December 1982, April 1983, October 1984 and April 1985 are used in numerical integration as the basic flow in a non-linear critical-layer model. The subtropical high is extensive and limited in number if simulated with the basic flow in December 1982 and April 1983. It consists of 2 to 3 cells that move westward at an oscillatory periods of 1~ 2 months. The subtropical high, simulated with the basic flow in October 1984 and April 1985, is weak and small in coverage, or distributed in strips that contain up to 4 cells. The high, merged or split over a short time, is moving westward. The years 1982 ~1983 are a process of El Niño while the years 1984-1985 one of La Niña. It is known from the chart of energy flux that it oscillates by a much larger amplitude and longer period in the El Niño year than in the La Niña year. All the results above have indicated that the basic flow in the El Niño year is enhancing the subtropical high lagging by about 4 months and that in the La Niña year is decaying it. It is consistent with the well-known observational fact that the SSTA in the equatorial eastern Pacific is positively correlated with the extent and intensity of the subtropical high in west Pacific lagging by 1~2 seasons. The result is also important for further study of the formation, maintenance and oscillation of the subtropical high.

Key words: non-linear critical layer; subtropical high; El Niño event; basic flow

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## I . INTRODUCTION

Being a deep and warm high pressure system at the middle and lower layers of the subtropical high in the troposphere, the west Pacific subtropical high is an important factor that affects the rainy season, heavy rain and typhoon track in China through the changes in the location and intensity. For instance, the subtropical high was especially strong and extensive in the winter 1982 ~1983 and caused anomalously more precipitation in south China, with most of the region receiving 350 ~500 mm, some between 600 mm and 700 mm, in December through February. The amount is generally more than twice as much as the multi-year mean and more than three times as much as it in central Guangdong and eastern Guangxi, causing a winter flood in south China (Wang and Zhao, 1984). The west Pacific subtropical high began weakening in 1984 ~1985 with unstable condition and large fluctuation in north-south oscillation. The period corresponds to a time with normal records of climate (Yang and Yuan, 1985; Jiang and He, 1986).

Being a reflection of joint action by multiple factors, the circulation system of the subtropical

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high is found to have a significant and stable correlation that is both positive and lagging by some months with the mean SST in the eastern equatorial Pacific (0° ~10°S, 180° ~90°W). In the El Niño period (high SST), the west Pacific subtropical high is stronger than the average year with a larger area and westward extension. In the La Niña year (low SST), however, it is weaker than the average year with a smaller area and eastward location. The difference between the El Niño and the La Niña years well extends to the following summer from autumn, most pronounced from November to the coming May, regarding the intensity, area index and the point of westward-going ridge of the subtropical high (Wang and Zhao, 1984). The El Niño process from September 1982 to September 1983 is the strongest since 1951 and the La Niña process from October 1984 to September 1985 is a weak process. On the mechanism with which the El Niño event affects the subtropical high, Chen (1983) points out that the north Pacific subtropical high interacts with the equatorial eastern Pacific SST through the following possible way of strengthened (weakened) anticyclone in southeastern North Pacific → increased (decreased) equatorial easterly component → dropped (risen) equatorial eastern Pacific SST → weakened (strengthened) Hadley cell → weakened (strengthened) subtropical high in central North Pacific and dropped (risen) air pressure with the influence extending eastward (shrinking westward) → weakened (strengthened) subtropical anticyclone in the southeastern North Pacific. Having influence, feedback and adjustment among themselves, they form an enclosed negative process that restrains each other. According to their computation, the west Pacific subtropical high exerts obvious lagging response on the changes of the equatorial SST: the subtropical high starts strengthening about 1 ~ 2 seasons after the onset of ocean surface warming and vice verse. Computing the monthly PNA index for each of the El Niño and La Niña years, we know that there is a significant tele-correlation between the atmosphere in mid- and high- latitudes and the anomalous SST in the equatorial eastern Pacific, particularly so in winter (Zhao, Zhang and Ding, 1990). Huang (1986) studies the physical cause of formation for the statistical results above from the point of theoretic analysis and numerical simulation. The result shows that anomalous behavior of the heating source over the tropical Pacific can cause similar response in the PNA pattern of the general circulation in Northern Hemisphere, which is also contributed by the transportation of quasi-stationary planetary waves. Huang (1991) further points out that the different perturbation anomalies will be resulted if the basic flow changes, even if there is the same anomalous heating source in the tropical eastern Pacific.

As the subtropical high is between the boundary between the easterly and westerly, $\bar{u} = c = 0$ is a critical layer at it. Therefore, Lu, Wang and Peng (1995) put forward that the so-called "Kelvin cat's eye" induced on the non-linear critical layer by the forcing of the northern boundary may be a new physical mechanism for the formation of the subtropical high. In view of a possible larger weight by the tropics on the formation, maintenance and oscillation of the subtropical high, Lu and Tao (1996) address the effects of stationary forcing along its southern boundary on the "Kelvin cat's eye" on the non-linear critical layer.

It is then reasonable to apply the basic flow for the El Niño and La Niña years in a non-linear critical layer model with constant forcing on the southern boundary. The attempt is to simulate the evolution of anticyclonic circulation induced on the critical layer by basic flow. The numerical simulation is performed using the monthly mean zonal $U$ field data at 500 hPa within the region of the subtropical high in December 1982, April 1983, October 1984 and April 1985.

## II SCHEME OF NUMERICAL EXPERIMENT

Below is shown a numerical experiment model that takes the nondimensional and nondivergent barotropic vorticity model as the non-linear critical layer:

$$\frac{\partial}{\partial}\nabla^2\phi+\bar{u}\frac{\partial}{\partial x}\nabla^2\phi+(\beta-\bar{u}_{yy})\frac{\partial\phi}{\partial x}+\varepsilon\left[J(\phi,\nabla^2\phi)-\overline{J(\phi,\nabla^2\phi)}\right]=0 \tag{1}$$

$$\frac{\partial\bar{u}}{\partial x}=-\varepsilon^2\frac{\partial}{\partial y}\overline{uv} \tag{2}$$

where $\phi$ is the stream function of the perturbation, $\bar{u}$ is the basic zonal airflow, $\overline{(\ )}$ is the zonal mean and $0<\varepsilon\leqslant 1$, $\nabla^2=\frac{\partial^2}{\partial y^2}+\delta^2\frac{\partial^2}{\partial x^2}$, $\delta^2=\frac{L_y^2}{L_x^2}$. The current work uses the values of $\varepsilon=0.02$, $\delta=0.4$, $\beta=1.6$, and $\bar{u}=-\frac{\partial\phi}{\partial y}$, $\bar{v}=\frac{\partial\phi}{\partial x}$; the stream function is written as

$$\phi=-\int_0^y\bar{u}(y,t)\mathrm{d}y+\varepsilon\phi(x,y,t) \tag{3}$$

Eqs. (1) and (2) are reduced to a differential form and numerically integrated. Detailed model design is presented in Lu et al. (1996).

(1)The domain of integration is $0\le x\le 2\pi$, $-1.5\le y\le 2.5$, $\delta x=\frac{2\pi}{70}\approx 0.09$, $\delta y=0.05$.

(2)The equation of second-order central difference is applied to derivation of all except for $\bar{u}_{yy}$ that uses the fourth-order difference format

$$\overline{u_j''}=\left[16(\bar{u}_{j+1}+\bar{u}_{j-1}-2\bar{u}_j)-(\bar{u}_{j+2}+\bar{u}_{j-2}-2\bar{u}_j)\right]/12\delta y^2 \tag{4}$$

For the Jacobi operator, the Arakawa model is taken, which ensures the conservation of total vorticity, kinetic energy and enstrophy.

(3)The time-filtering scheme is used in the time integration which initializes with the Eular backward difference before being applied in each step with central difference added to a weak time filtering. The time step takes $\delta t=0.03$, or

$$\begin{cases}\phi_*^{n+1}=\phi^{n-1}-2\delta t\phi_{t*}^n\\ \phi^n=\phi_*^n+0.5v(\phi_*^{n+1}+\phi^{n-1}-2\phi_*^n)\end{cases} \tag{5}$$

$\bar{u}$ is similar to $\phi$, which takes $v=0.05$.

(4)For the boundary and initial boundary, a constant boundary condition is added at the southern edge:

$$\phi=\begin{cases}(t/t_s)\cos kx & t<t_s\\ \cos kx & t\ge t_s\end{cases} \tag{6}$$

where $k=1$, $t_s=96\delta t$; at the northern edge, $\bar{u}$ equals $\phi$ on the sub-boundary and boundary.

The initial value of $\phi$ takes Eq.(6) on the southern boundary with zero in other portions, or

$$\phi(x,y)=0,\quad -1.5<y\le 2.5 \text{ when } t=0 \tag{7}$$

(5)Reducing Eq.(1) into the Poisson equation of

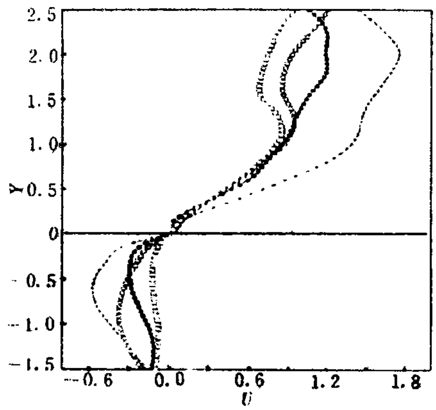


Fig.1 Total stream function field in the El Niño year (a) December 1982; (b) April 1983

$$\nabla^2 \frac{\partial \phi}{\partial t} = F \tag{8}$$

Eq.(8) can be derived by the method of iteration by over relaxation with the relaxation coefficient of 0.75.

(6) Scheme of numerical experiment (Fig.1)

Scheme Ⅰ: the basic flow takes the form of December 1982 when $t=0$ (shown by multiplication sign);

Scheme Ⅱ: the basic flow takes the form of April 1983 when $t=0$ (shown by hollow circle);

Scheme Ⅲ: the basic flow takes the form of October 1984 when $t=0$ (shown by solid circle);

Scheme Ⅳ: the basic flow takes the form of April 1985 when $t=0$ (shown by hollow diamond).

It is obvious that the westerly is larger in the El Niño year than in the La Niña year in terms of the maximum value. It is also confirmation of the fact that there is activity of large-scale westerly (easterly) in the El Niño (La Niña) year.

## III. RESULTS OF NUMERICAL SIMULATION EXPERIMENTS AND ANALYSIS

In the current work, a 2000-step integration is done with the four schemes above by taking corresponding nondimensional time $T=60$. With the characteristic scale in the $y$ direction taken as $L_y = 10^3$, then $L_x = L_y/\delta = 2.5\times10^3$km; when the characteristic speed $U=15$m/s we have dimensional time of $t^* = L_x t/U \approx 46.3t$(h); the 2000 steps correspond to a length of $t^* = 116$d, or about 4 months.

Integrating respectively the basic flow for the El Niño year and La Niña year yields detailed charts of total stream function fields as in Fig.2 and Fig.3. The domain of plotting goes from $0 \le x \le 2\pi$ (denoted as $0 \le x \le 2$ in the figure) to $-0.1 \le y \le 1.0$. Comparing the figures, we know that the "Kelvin cat's eye" (i.e. the anticyclonic circulation) generated in the El Niño scheme is both large and limited in number (2 to 3 generally), with the length and width being $x = \frac{2}{3}\pi \sim \pi, y = 1.1 \sim 2.0$. They respectively correspond to east-west length of $x^* = L_x x = (5.23 \sim 7.85)\times10^3$km and north-south width of $y^* = L_y y = (1.1 \sim 2.0)\times10^3$km, in dimensional measurement. On the other hand, the anticyclonic circulation generated in the La Niña scheme is both weak and numerous, with the length and width being $x = 0.5\pi, y = 0.3 \sim 0.9$, correspond to east-west length of $x^* = L_x x = 3.93\times10^3$km and north-south width of $y^* = L_y y = (0.3 \sim 0.9)\times10^3$km, in dimensional measurement.

1. *Variation of intensity, movement and shape of "Kelvin cat's eye" in the four schemes*

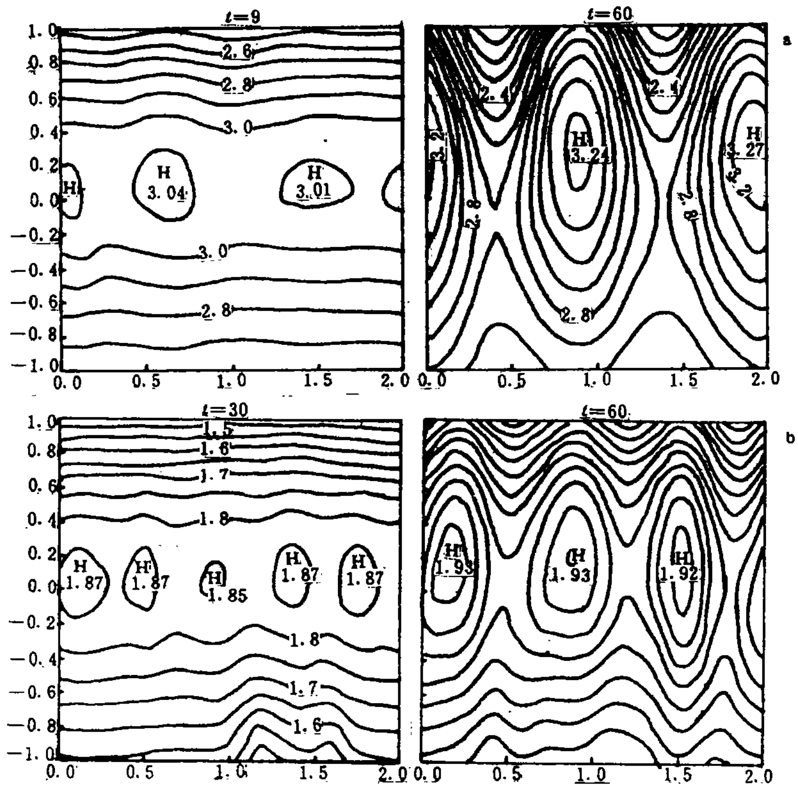


Fig.2 Total stream function field in the El Niño years a. December 1982. b. April 1983

1) VARIATION OF THE SHAPE IN STREAM FUNCTION FIELD

Scheme Ⅰ: Over the course $t$=15 ~ 20, there have been two "cat's eye" cells in the flow field that take generally the same shape, an ellipse with the major axis in the $y$ direction. It is known from careful study that the two cells are not equally strong and over time weaken to a near circular with much similarity in intensity and shape before strengthening to be unequally strong again. Oscillatory variation has occurred in the shape. The "cat's eye" extends for about 2000 km in the $y$ direction and about 7850 km in the $x$ direction.

Scheme Ⅱ: Over the time from the generation of the "cat's eye" to the point as $t$=18, the north-south spatial span has been small (about 300 km) and there are 3 – 4 high-value centers. Afterwards the span keeps increasing and the closed contours are getting denser and denser. By $t$=30, the "cat's eye" has merged into three centers that maintain until $t$=60. The north-south width the "cat's eye" has now increased to 1100 km, the greatest in this direction, with the length in the $x$ direction being about 5230 km.

By $t$=60, or when the integration steps into its fourth month, the "cat's eye" is about 50% to 100% larger in the $x$ length and $y$ width for the cell in Scheme I than in Scheme II. In December 1982, the increase of SST is on its peaks in this El Niño event, which is followed by decreasing positive anomalies of the SST. By April 1983, the positive SST anomalies have reduced by large extent. It is then obvious that by a lagging of about 4 months the spatial size of the "cat's eye" as

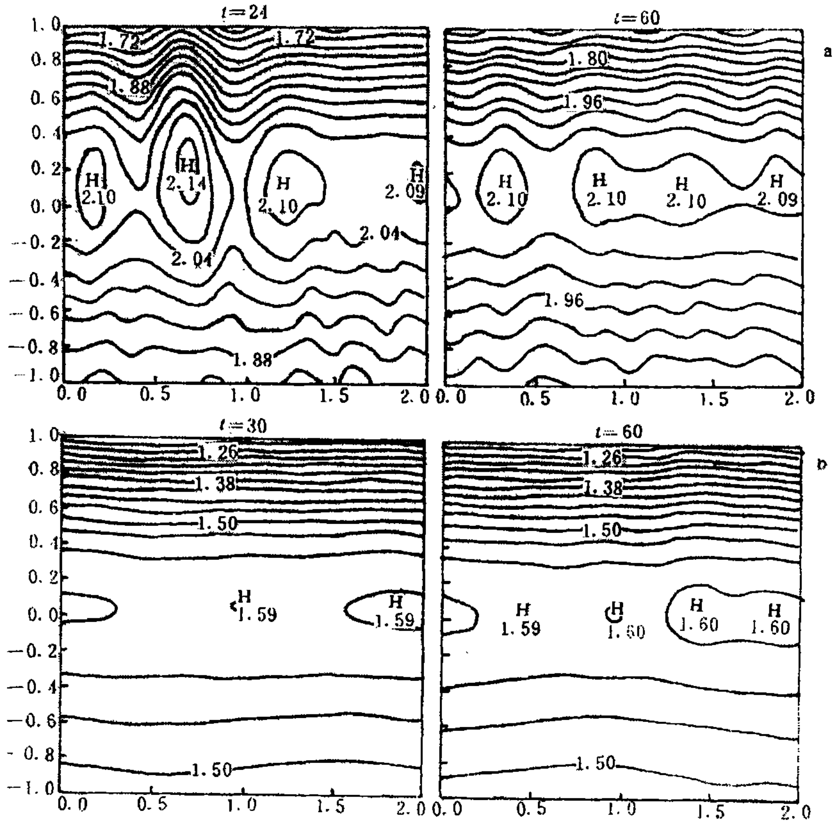


Fig.3 As in Fig.2 but for the La Niña years

induced by the basic flow is proportional to the positive anomaly of the SST in the El Niño event. In other words, a large positive SST anomaly in an earlier period is corresponding to a large "cat's eye" about four months later and vice versa.

Scheme III: In the initial period of the generation, the "cat's eye" is only a positive-value center. Two such centers appear as $t$=3, three appear as $t$=7.5, 25.5, 27, 28.5, 46.5, 57, and 58.5 and four appear in other parts of the time. The appearance of four positive-value centers is a major feature. The "cat's eye" can extend to a width of about 900 km in the $y$ direction as $t$=19.5 ~ 30, which decreases over time. It is about 500 km at $t$=45 and about 400 km at $t$=60. The length in the $x$ direction is then about 3930 km.

Scheme IV: There is only one high-value center in the flow field at $t$=1.5. Two centers appear as $t$=6, 21 ~ 24, 27 ~29, 43.5 ~ 48 and 54. Three appear as $t$=7.5 ~ 19.5, 40.5, 51 ~ 52.5. Four appear as $t$=25.5, 55.5 ~ 60. Only one center appears as $t$=42, 49.5. The "cat's eye" rapidly splits and converges with oscillation. The width in the $y$ direction is the smallest of all the schemes. It is only about 300 km in the $y$ direction as it varies from $t$=6 all the way to $t$=60 while the length in the $x$ direction is the same as in Scheme III.

As $t$=60, the "cat's eye" cell is about 30% larger in the $y$ direction in Scheme III than in Scheme IV. The length is the same. When the La Niña began in December 1984, a negative SST anomaly (or a mild fall of temperature) occurred in the equatorial eastern Pacific. The La Niña-associated temperature fall has reached a large value in April 1985. It is then clear that by a lagging of about 4 months the spatial size of the "cat's eye" as induced by the basic flow is inversely proportional to the initial absolute value of the negative anomaly of the SST in the La Niña event. In other words, a large negative SST anomaly in an earlier period is corresponding to a small "cat's eye" about four months later and vice versa.

It is known from the analysis above that the number of the "cat's eye" cells decreases (to two to three) in the flow field in the El Niño year corresponding to $t$=60. The north-south range is large. It is in contrast to the La Niña year when there are "cat's eye" cells, sometimes as many as four, whose north-south range is small. It is indicated in the four schemes that a large SST anomaly at the initial time of the basic flow is followed by a large "cat's eye" months later and otherwise is true.

2) VARIATION OF THE INTENSITY IN STREAM FUNCTION FIELD

Scheme I (December 1982, Fig.2a): At $t$=7.5, the "Kelvin cat's eye" is formed and there are two closed centers in the flow field; the centers soon split into three at $t$=9 with the maximum of 3.13 at the center of the "cat's eye"; the three centers merge into two at $t$=15 and two anticyclones are maintained until the point when $t$=60. By the time, the maximum becomes 3.27 for the center of the "cat's eye", a 4.5% increase compared with one at $t$=9. Its intensity is as much as 3.30, increasing by 5.4% compared with one at $t$=9.

Scheme II (October 1983, Fig.2b): At $t$=1.5, the "cat's eye" is formed with a central intensity of 1.88; the intensity rises to 1.93 at $t$=60, increasing by 2.7% as compared to the point when $t$=1.5. As $t$=60 (except for the integration of 4 months), the intensity of the "cat's eye" cell in Scheme I is about 70% larger than the ones in Scheme II.

Scheme III (October 1984, Fig.3a): At $t$=1.5, the "cat's eye" is formed with a central intensity of 2.08; it strengthens with time, becoming the largest (2.14) at $t$=24, a 2.9% increase than at the initial time. The "cat's eye" is relatively strong during the period when $t$=19.5 – 30 and it is relatively weak when $t$=31.5 ~ 60. The central intensity is 2.10 at $t$=60, which has increased by 0.96 % than at the initial time.

Scheme IV (April 1985, Fig.3b): At $t$=1.5, the intensity of the "cat's eye" is 1.59 and stays there until the point when $t$=60. Over the time, it varies little and rises to 1.60 at the highest peak, just a 0.6% increase than it is when $t$=1.5 at the initial time. At $t$=60, the cell intensity in Scheme III is 30% larger than it is in Scheme IV.

It is concluded from the analysis above that the intensity of the "cat's eye" in Scheme I is the strongest at $t$=60 or about four months into the integration, about 70% larger than in Schemes II and III and about 106% larger than in Scheme IV. The intensity in Scheme II is about 21% larger than in Scheme IV, though in much similarity with Scheme III.

3) VARIATION OF THE MOVEMENT IN STREAM FUNCTION FIELD

Scheme I: The "cat's eye" is moving westward steadily at about $2\pi/15$, being equivalent to 6.3 m/s. If the process in which the "cat's eye" moves out of the west boundary and returns from the east boundary back to the original place is taken as a period, then it is 15, which is 29 days in the dimensional measurement. That is to say: the oscillatory period is about a month. The "cat's eye" is born on the critical line before strengthening and moving northward, with the greatest displacement of 300 km ($t$=57). At $t$=60, the cell has moved northward by about 200 km.

Scheme II: The "cat's eye" is moving westward steadily at about $2\pi/33$, being equivalent to 2.9 m/s, which is about half the one in Scheme Ⅰ. The oscillatory period is about 64 days (or two months). The "cat's eye" is born on the critical line before strengthening and moving northward, with the greatest displacement of 400 km. At $t$=60, the cell is still about 200 km north of the original place, which is the same as in Scheme Ⅰ.

Scheme Ⅲ: The "cat's eye" is moving westward at a unspecified speed due to rapid convergence and split of individual cells. The centers can be as much as 200 km away from the critical line. At $t$=60, the "cat's eye" is free from any north-south displacement.

Scheme Ⅳ: The "cat's eye" is also moving westward at a unspecified speed due to rapid convergence and split of individual cells. The center is about 50 km north of the critical line. At $t$=60, the "cat's eye" is free from any north-south displacement, the same as in Scheme Ⅲ.

It is concluded from the analysis above that there is obvious westward movement of the "cat's eye" in the El Niño year with the east-west oscillatory at a period of 30 ~ 60 days and a large north-south oscillatory. The "cat's eye" in the La Niña year is moving faster to the west with a smaller north-south oscillation. At $t$=60, the "cat's eye" is 200 km northward in the El Niño year but it takes no displacement north-south in the La Niña year.

2. *Variation of energy in the nonlinear critical layer*

The $y$ component of the $EP$ flux, $-\overline{u'v'}$, denotes the direction of transportation of the wave energy in the $y$ direction. $[-\overline{u'v'}]=[-\overline{u'v'}]_{+}-[-\overline{u'v'}]_{-}$ is the convergence and divergence of the wave energy in the $y$ direction. The subscripts "+" and "–" are the values north and south of the critical line. As $[-\overline{u'v'}]<0$, energy converges in the critical layer which absorbs it; as $[-\overline{u'v'}]>0$, energy is over reflected; as $[-\overline{u'v'}]=0$, energy is ideally reflected at an ideal amplitude. Next is the study of energy flux in the El Niño and La Niña years with the southern boundary on $y$=–1.5, –1.45 and –1.4.There is not any constant forcing one the northern boundary, so $\overline{u'v'}=0$ on the northern boundary. Then, $[-\overline{u'v'}]=(\overline{u'v'})_{y=-1.5}$. Therefore, the positive and negative values in Fig.4 are standing for the over reflection, or transportation of energy to the "cat's eye" from the basic flow, and the absorption, or transportation of energy to the basic flow from the "cat's eye". An ideal reflection means that there is no transportation of energy between them. It is known from the figure that $(-\overline{u'v'})$ decays in oscillation near the zero line, followed first by over reflection in the critical layer and then by the ideal reflection. The process goes with absorption and weak over reflection following, etc. The case is similar as $y$= –1.45, –1.4. The figure is omitted.

Schemes Ⅰ and Ⅱ: The over reflection first appears in the critical layer in Scheme Ⅰ — the "cat's eye" obtains energy from the basic flow and keeps developing until $t$=32 when there are over reflection and absorption, i.e. the "cat's eye" transports energy, which is somewhat weakened, to the basic flow. By the time $t$=47, the second ideal reflection and over reflection take place in turn until $t$=60 when the "cat's eye" gets energy from the basic flow to strengthen. For the critical layer in Scheme Ⅱ, the over reflection is also the first incidence with the largely same amplitude as in Scheme Ⅰ. The "cat's eye" keeps increasing until the time $t$=40 when the ideal reflection take place, which is followed by the absorption until $t$=60. The "cat's eye" is weakened by the time.

Scheme Ⅲ and Ⅳ: The energy flux of the two schemes varies in almost the same pattern. They have the over reflection first when the "cat's eye" strengthens by having energy from the basic flow. At $t$=18, they both have the first ideal reflection and absorption, i.e. the "cat's eye" transport energy to the basic flow. At $t$=38, they both have the ideal reflection at the same time,

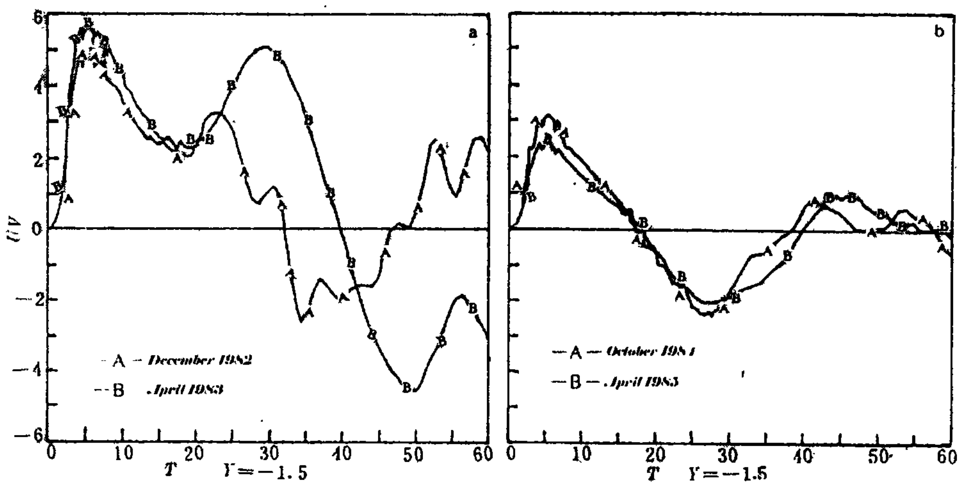


Fig.4 Curves of energy flux over time in the El Niño year (a, December 1982) and the La Niña year (b. April 1983)

which is followed by a mild over reflection. It tends to act like the ideal reflection with the time diminishing until the "cat's eye" moves to a constant state.

It is obvious that the energy flux oscillates with almost twice as much the amplitude and the over reflection is almost twice as long on average in the El Niño year as that in the La Niña year. As a result, the energy obtained from the basic flow in the El Niño year is almost twice as much and long as that in the La Niña year. In the El Niño year, the basic flow corresponding to the peak positive SST anomalies in the equatorial eastern Pacific is such that the "cat's eye" obtains more but energy than it does from the flow associated with the SST anomalies off the peak periods, though it gives less energy.

## Ⅳ. CONCLUDING REMARKS

a. By a lagging of about 4 months, the spatial size of the "cat's eye" as induced by the basic flow in the El Niño and La Niña years is proportional to the SST in the equatorial eastern Pacific. In other words, a large SST anomaly in an earlier period is corresponding to a large "cat's eye" about four months later and vice versa. Therefore, as the positive SST anomalies reach the peak values in the region in the El Niño year, the "cat's eye" will be the greatest by a lag of about 4 months; as the negative SST anomalies reach large values in the region in the La Niña year, the "cat's eye" will be the smallest by a lag of about 4 months. Its spatial domain is between the two extremes in other periods.

b. By a lagging of about 4 months, the intensity of the "cat's eye" as induced by the basic flow in the El Niño and La Niña years is corresponding to a peak or large positive or negative SST anomaly in the equatorial eastern Pacific, being the largest or smallest, respectively. It is between the two extremes in other periods.

c. By a lagging of about 4 months, the "cat's eye" as induced by the basic flow in the El Niño year has a larger north-south movement than it would in the La Niña year.

d. The "cat's eye" gets nearly as twice energy from the basic flow in the El Niño year as it does in the La Niña year.

In summary, the basic flow strengthens the subtropical high in the El Niño year but decays it in the La Niña year by a lagging of about 4 months. Because the initial basic flow corresponds to the Hadley cell at the initial time, the initial positive and negative SST anomalies in the equatorial eastern Pacific is included as they respond to diabatic heating of the atmosphere. The effects of strengthening and decaying the subtropical high by a lag of 4 months are in fact an indication that the earlier positive and negative SST anomalies in the equatorial eastern Pacific in the El Niño and La Niña years are strengthening and decaying the subtropical high by a lag of 4 months. It is consistent with the well-known observational fact that the SSTA in the equatorial eastern Pacific is correlated with the extent and intensity of the subtropical high by a lag of 1 ~ 2 months. The result by our work is of importance to further study of the formation, maintenance and oscillation of the subtropical high.

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