The Influence of Tibetan Plateau on the Interannual Variability of Atmospheric Circulation over Tropical Pacific

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ABSTRACT

An atmospheric general circulation model (AGCM) with 9 sigma levels in the vertical and rhomboidal trunction at wave number 15 in the horizontal is run for 10 years with and without the Tibetan Plateau respectively (called TP and NTP experiment). The result simulated is used to investigate the influence of the Tibetan Plateau on the interannual variability of atmospheric circulation over tropical Pacific. It is found that the spatial and temporal distributions of the interannual variability of the wind field over tropical Pacific in TP experiment and those in NTP experiment agree with each other except for the intensity, and both of them are consistent with observations well. Further analysis shows that in El Nino period the Tibetan Plateau strengthens the intensity of El Nino event, while in La Nina period it weakens the intensity of La Nina.

Key words: AGCMs, Tibetan Plateau, Interannual variability, Tropical Pacific

I. INTRODUCTION

El Nino / South Oscillation (ENSO) is the strongest signal found up to now in the ocean and atmosphere interannual variability, higher than the climatic noise level. Ocean–atmosphere interaction, especially ENSO, has become a popular topic of today's climatic dynamics. Studies show that the air–sea interaction in the tropics is much more active than that in other areas. Anomalies in the tropical oceans exert more influence on the atmospheric circulation than the middle–latitude oceans do and has prominent contribution to the interannual climate variability (Charney and Shukla, 1981). Therefore, the researches of ocean–atmosphere interaction in tropics are of great importance. In the ocean–atmosphere system, the sea surface wind is the most important factor that determines the sea surface currents. In the oceanographic model of El Nino proposed by Bjerknes (1966), Namias (1969) and Wyrtki (1975), the relaxation of the trade wind (or strenthening continually then relaxing) is regarded as the elementary condition of the onset of El Nino; Rassmusson and Carpenter (1982) also devoted much attention to the features of the sea surface wind, rainfall in tropics and ITCZ, etc. which are associated with the sea surface temperature anomalies (SSTA) in their meteorological model of El Nino. The oceanographic theory we have by now mainly discusses the response of ocean to the variation of sea surface wind stress. The Kelvin waves excited by the equatorial westerly anomalies can explain many aspects of El Nino in observations. In Philander's (1984) theory of instable air–sea interaction in the tropics, the intensity variation of the trade wind was also been emphasized. Say briefly, anomalous variation of the tropical wind is not only an elementary condition to the happening of El Nino, but also an important signal of the ENSO cycle. Detailed analysis of its interannual variability is neccessary for the ENSO study and its prediction.

On the other hand, numerical simulations indicate that, as the largest orography in the world, the Tibetan Plateu has great influence on the global atmospheric circulation, especially the Asian monsoon (Manabe and Terpstra, 1974; Hahn and Manabe, 1975). Then the question that is still open is whether the interannual variability of the tropical wind is also affected by the Tibetean Plateau. Answer to this question will help us gain a further sight into the relationship of Tibetan Plateau and ENSO and climate change.

Model and contrast experiments are described in section II. The data are mentioned in Section III. Section IV displays the results of TP and NTP experiments and the comparision with observation. Conclusions and discussion are presented in section V.

II. MODEL AND CONTRAST EXPERIMENTS

In this paper, we use an atmospheric general circulation model(AGCM) with 9 sigma levels in the vertical and rhomboidal trunction at wave number 15 in the horizontal which was developed by Bourke et al. (1978) and modified by Simmonds (1985), Lin (1986) and Wu (1996). Based on the primitive equations, model prediction employs divergence, vorticity and thermodynamic equations as well as a prognostic equation for water vapor. The equation for the vertical component of velocity is replaced by a diagnostic relationship on the assumption that the motions are in hydrostatic equilibrium. It is noteworthy that a stratified reference atmosphere is incorporated for temperature and gravitational potential and the standard temperature can be described as

$$C_0{}^2 = \frac{R^2 \bar{T}(P)}{g} \left(\frac{g}{c_p} + \frac{\partial \bar{T}(P)}{\partial Z} \right) = \text{constant}$$

Using the deviations from the reference atmosphere as the model variables, the error caused by the real terrain spectral trunction can be reduced greatly (Zeng, 1979; Chen, 1987). The physical processes in this model include the absorption of solar radiation and the long-wave component of terrestrial radiation, a boundary layer parameterization based on the theory of Monin-Obukhov and a convection adjustment scheme of Manabe, sub-grid horizontal and vertical diffusion, roughness of the underlying surface, ice and snow cover and the effects of topography are also considered. The surface temperature is obtained by the heat balance equation. Physical processes and nonlinear terms are calculated in grid space using the full transformation method of Eliassen and Mechehauer. The semi-implicit scheme with time step 30 minutes is used for time integration.

The contrast experiments are carried out using the above AGCMs with realistic sea surface temperature and sea ice from Jan. 1979 to Dec. 1988. More detailed description of the model and SST and sea ice used in the model can be found in Wu (1996).

(1) NTP experiment (without Tibetan Plateau)

In the NTP model, the Tibetan Plateau is eliminated(grid altitude less than 100m in this region). The NTP model is initialized by running a so-called "January model" with all external forcings (climatologically, same as the model with the Tibetan Plateau) fixed on January 15th for 9 months and using the averaged field of the final 3 months as the initial state for NTP simulation. Run the AGCMs without the Tibetan Plateau for 10 years. It must be pointed out that the snow cover and albedo over the Tibetan Plateau are modified correspondingly.

(2) TP experiment

TP experiment is just similar to the NTP one but using the real orography of the Tibetan Plateau.

III. DATA

1. *Model Output Data*

Monthly mean wind fields at 850 hPa and 300 hPa in the 10-year simulations with and without Tibetan Plateau.

2. *Observational Data*

Global monthly mean wind fields at 850 hPa from Jan. 1980 to May. 1994 with horizontal resolution of 5° latitude by 5° longitude.

In order to discuss the interannual variability, a quadrupole low pass filter (Kaylor, 1977) is used to filter the high frequency signals with period shorter than one year from the above data.

IV. INTERANNUAL VARIABILITY OF THE TROPICAL PACIFIC WIND IN TP AND NTP EXPERIMENTS AND THEIR DIFFERENCE

1. *Zonal wind Anomalies Along the Equator*

The time-longitude cross section of the zonal wind anomalies at 850 hPa along the equator is shown in Fig.1 (unit: m / s). The shaded area denotes the positive value meaning westerly anomalies. Fig. 1(a) is the observational result, Fig. 1(b), 1(c) represent the result from TP experiment, NTP experiment and the difference (TP-NTP) respectively. Comparing Fig. 1(b), (c), (d) with Fig.1(a), we can see that both TP simulation and NTP simulation bear resemblance to observation in pattern although their intensities are somewhat underestimated. Two El Nino(1982 / 83, 1986 / 87) and two La Nina (1984 / 85, 1988 / 89) events are reproduced successfully either in TP experiment or in NTP experiment.

Comparing Fig.1(b) with Fig.1(c), it clearly shows that the distributions of zonal wind anomalies at low level with and without the Tibetan Plateau are similar to each other except for intensity. From their difference (see Fig.1(d)) we can find that, since the beginning of 1982, a positive difference propagates eastward from western Pacific. Until Jan. 1983, there is still a large zonal positive area along the equator. The positive area moves eastward continually, but its intensity and range reduce gradually. By June-July 1983, almost the whole equatorial Pacific is occupied by negative difference. Note that at this time the westerly anomalies have not disappeared in NTP experiment (see Fig.1(c)). It lasts to end of 1983 about 1-2 months later than the observation and TP experiment. As for the 1986 / 87 El Nino process, the situation is similar. In Fig.1(d), a positive area propagates eastward from western Pacific since Jan. 1986, it reaches the date line in Jan. 1987 and dominates the central-eastern equatorial Pacific. Then it is weakened and replaced by negative value in July 1987, meanwhile the El Nino hasn't ended because the westerly anomalies still exist in Fig. 1(c). It is easy to understand that the difference of zonal wind anomalies between TP experiment and NTP experiment exactly reflects the impact of the Tibetan Plateau on the zonal wind anomalies. Positive (negative) difference suggests that the Tibetan Plateau strengthens(weakens) the westerly anomalies. According to the above analysis, we can find that during the occurring and developing period of El Nino (called the earlier period simply) and the prevailing period, the Tibetan Plateau increases the intensity of the westerly anomalies. As a result, El Nino is reinforced. However, during the later period of El Nino, it brings about the easterly anomalies and impels El Nino to end. This fact also can be found in Fig.1(b) and Fig.1(c): the westerly anomalies in TP experiment is stronger than that in NTP experiment during the developing

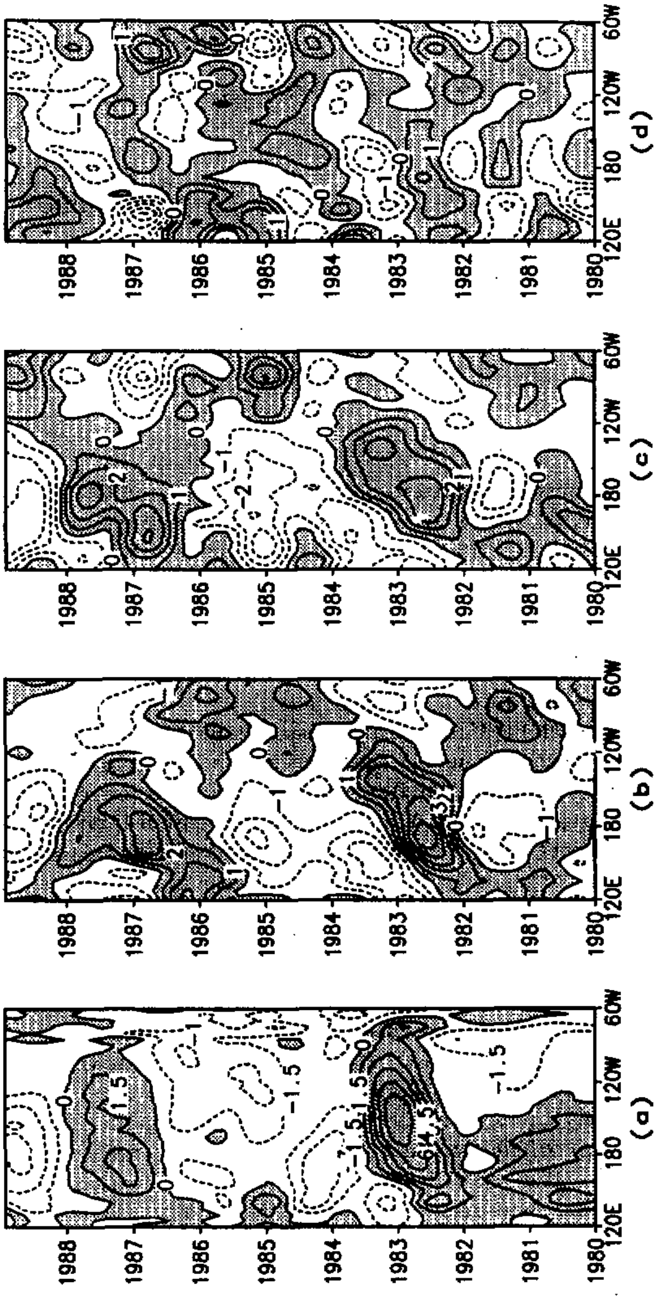

Fig. 1. Time evolution of zonal wind anomalies at 850 hPa along the equator. (a) observed; (b) TP; (c) NTP; (d) TP−NTP.

period, but opposite is the case during the later period of El Nino. El Nino ends slightly later in NTP experiment than in TP experiment.

As to the two La Nina processes(see Fig.1(d)), from the beginning of 1984 to the end of 1985, the zonal wind anomaly difference (TP−NTP) maintains positive. Although there is a small negative area in the western equatorial Pacific, it is too weak to cross the date line. This implies that the Tibetan Plateau strengthens the westerly or weakens the easterly anomalies during La Nina episode. In the 1988 / 89 event, the situation is similar and even more conspicuous. Since the beginning of 1988, strong westerly anomalies resulting from the Tibetan Plateau migrates and expands eastward. Therefore the Tibetan Plateau restrains the occurring and developing of La Nina. In fact, the two La Nina in NTP experiment are obviously stronger than those in TP experiment. Additionally, the westerly anomalies due to existence of the Tibetan Plateau impel La Nina to end during its later period.

Analogous analysis of meridional wind is done. Results show that the pattern of the time−longitude cross section in TP experiment and that in NTP experiment are also similar despite the difference in the intensity(figures not shown here).

2. Vector EOF of the Interannual Variability of Low Level Wind over the Tropical Pacific

With the aim of revealing the spatial and temporal features of the interannual variability of the tropical wind, vector EOF analysis of the observed wind anomalies at 850 hPa has been done. The time series and the spatial vectors of the first two modes are presented in Fig.2. The variance contribution of the first and second mode is 40% and 20% respectively and the third mode amounts for 11% of total variance (the figure of mode 3 is not given here). In Fig.2(a), the two El Nino and two La Nina events can be easily distinguished. In Fig.2(a′), westerly and southwesterly anomalies appear over central−western tropical Pacific and westerly and northwesterly anomalies dominate the eastern Pacific. Both the northeast trade wind in the Northern Hemisphere and the southeast trade wind in the Southern Hemisphere are weakened, resulting in the strengthening of equatorial westerly. Obviously, the first mode just represents the temporal and spatial structure of ENSO. In the second mode, the westerly anomalies mainly appear in western Pacific. It is beneficial for the westerly (easterly) anomalies to set up in western Pacific during the earlier stage of El Nino (La Nina).

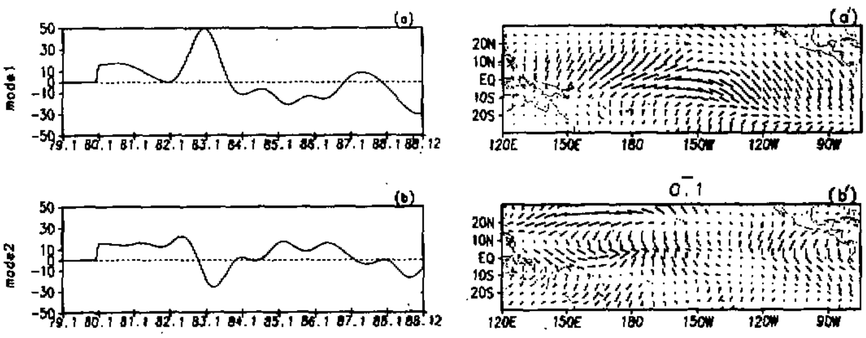

Fig. 2. Results of vector EOF for observed wind anomalies at 850 hPa. Only the first two modes are shown. 40% and 20% of the total variance are explained respectively. (a) Time series of mode 1; (b) Time series of mode 2; (a′) Spatial vector of mode 1; (b′) Spatial vector of mode 2.

Fig. 3 and Fig. 4 respectively give the time series and spatial structure of the first two modes in EOF of the simulated wind anomalies (left: TP experiment; right: NTP experiment). The first three modes in TP simulation contribute to 31%, 20% and 10% of total variance successively while in NTP experiment, 37%, 15% and 11% of total variance can be explained by the first, second and the third mode respectively.

Comparing the first mode in TP experiment with that in NTP experiment(see Fig.4(a) and 4(a′)), we can find that the spatial structure is basically identical and the westerly anomalies mainly appear to the west of 120°W, while in observation, it can reach 90°W (see Fig.2(a′)). Moreover, the phases of time series in TP experiment and NTP experiment generally keep synchronous although their peak values appear to be 3–4 months earlier than observation, and the simulations of 1982 / 83 El Nino are obviously weaker than observation. Fig.3(a) and Fig.3(a′) clearly show that the westerly anomalies in 1982～83 with Tibetan Plateau are stronger than those without the high mountain. But in 1984～85, the easterly anomalies in TP experiment are weaker than those in NTP experiment. According to the first mode of EOF, it can be clearly seen that the Tibetan Plateau strengthens the westerly anomalies during El Nino period and restrains the easterly anomalies during La Nina period.

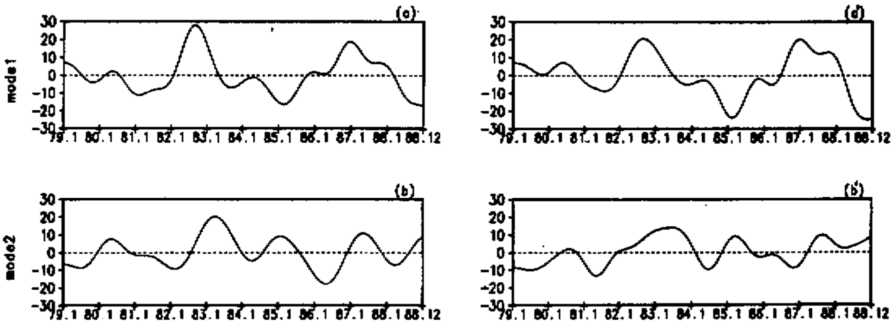

Fig. 3. Time series of the vector EOF for the simulated wind anomalies at 850 hPa. (a) Mode 1 in TP experiment (31% of total variance); (b) Mode 2 in TP experiment (20% of total variance); (a′) Mode 1 in NTP experiment (37% of total variance); (b′) Mode 2 in NTP experiment (15% of total variance).

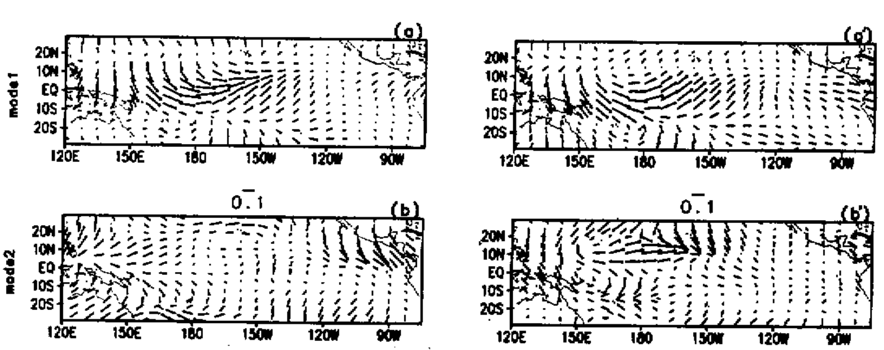

Fig. 4. Same as Fig. 3 but for the spatial structure.

From Fig.3(b) and 3(b′), we can find that the temporal evolution of the second mode in TP experiment and that in NTP experiment also keep in step rather well with one obvious peak appearing in 1983 and another one in 1987. However, they have great difference in the spatial structure. In NTP experiment strong westerly anomalies are located in the north of central Pacific (5°N ~ 20°N, 150°E ~ 150°W), while in TP experiment the westerly anomalies are very weak. It is just the westerly anomaly in NTP experiment that strengthens El Nino during its later period (Apr. ~ May in 1983 and Jul. ~ Aug. in 1984) and delays it to end. This fact also can be seen in Fig.1(b), 1(c).

In the light of above, the difference between TP experiment and NTP experiment during the later period chiefly lies in the second EOF mode. The Tibetan Plateau speeds up the ending of El Nino by affecting the second mode of low level wind.

3. *Composite Analysis*

In this section, composite analysis of the two El Nino and two La Nina cases have been done respectively and each one is partitioned into three stages or periods: earlier period, prevailing period and later period (see Table 1). Now we discuss the characteristics of the low and high level wind anomalies over tropical Pacific and the influence of the Tibetan Plateau in different stages.

Table 1. Composite of El Nino (or La Nina)

	earlier period	prevailing period	later period
El Nino(a. mon.)	1982.7+86.7	1983.1+87.1	1983.7+87.7
La Nina(a. mon.)	1984.7+88.7	1985.1+88.12	1985.12

During the earlier period of El Nino, the low level(850 hPa) and high level(300 hPa) wind anomalies in TP experiment are depicted in Fig.5(a) and Fig.5(a′). At low level, a large cyclonic circulation is located over the northern Pacific (centered at 20°N, 160°W) and another one in southern Pacific to the south of 30°S. As a result, the northeast trade wind in Northern Hemisphere and the southeast trade wind in Southern Hemisphere are weakened while the equatorial westerlies are intensified (here the shaded area denotes $\Delta u > 0$). At high level, two anticyclonic circulations appear at either side of equator centered at 15°N, 150°W and 15°S, 150°W respectively. The equatorial easterlies are enhanced. Obviously the wind anomalies in tropics have a baroclinic structure. The result in NTP experiment resembles that in TP experiment (see Fig. 5(b), 5(b′)). The difference of them (displayed in Fig.5(c), 5(c′)) provides a further indication that the Tibetan Plateau intensifies the westerly anomalies in central–western Pacific at low level as well as the easterly anomalies at high level.

During the prevailing period of El Nino, the low level westerly anomalies both in TP and NTP cases get enhanced and extend to 120°W (see Fig.6(a),6(a′)). At high level, two anticyclonic circulations are symmetrically situated about equator maintaining strong equatorial easterly anomalies (shown in Fig.6(b),6(b′)). The difference between TP experiment and NTP experiment indicates that the westerly anomalies dominating over the central–eastern Pacific at low level and the easterly anomalies at high level are intensified by the Tibetan Plateau (see Fig.6(c), 6(c′)).

During the later period of El Nino, at low level, the northwest Pacific high and the Australia high regain their vigor and the western tropical Pacific is under the control of

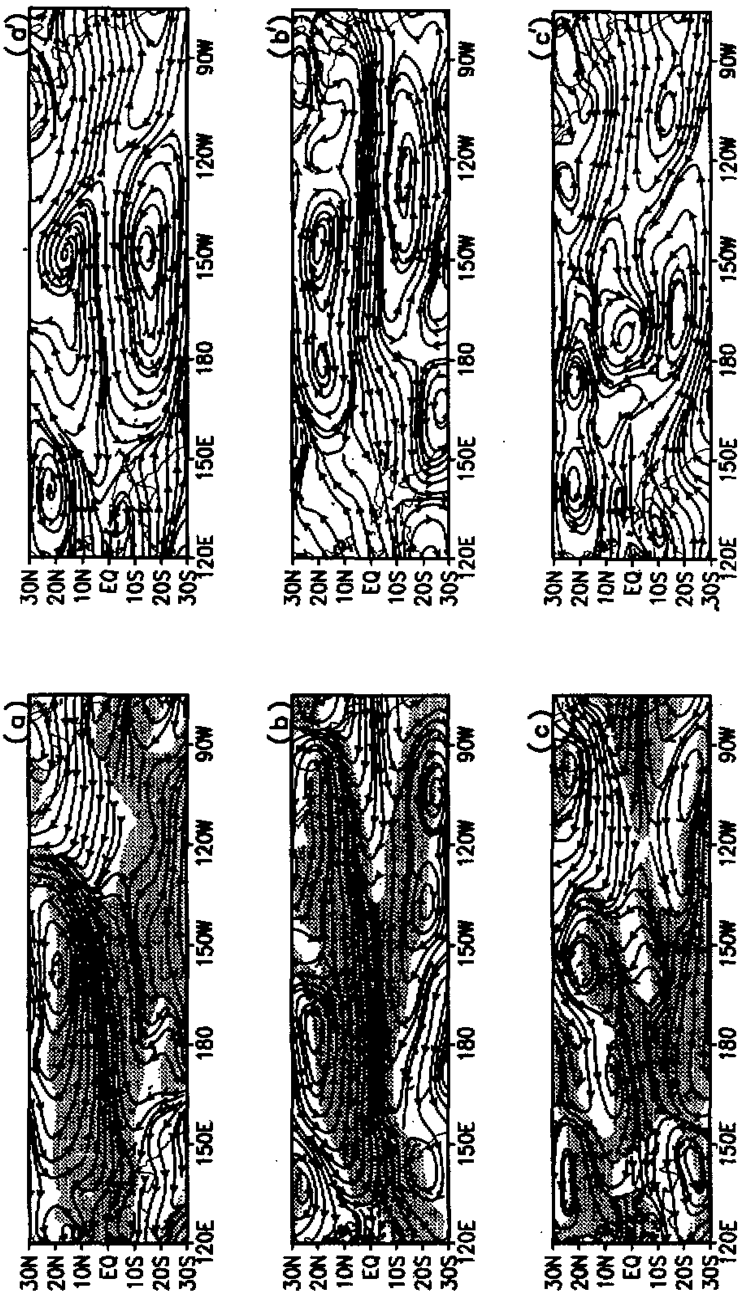

Fig. 5. Anomalous circulation in tropics and their difference between TP and NTP experiment during the earlier stage of El Nino. (a) Anomalous circulation at 850 hPa in TP experiment; (b) Anomalous circulation at 850 hPa in NTP experiment; (c) Difference between (a) and (b); (a'), (b'), (c') are same as (a), (b), (c) respectively but at 300 hPa.

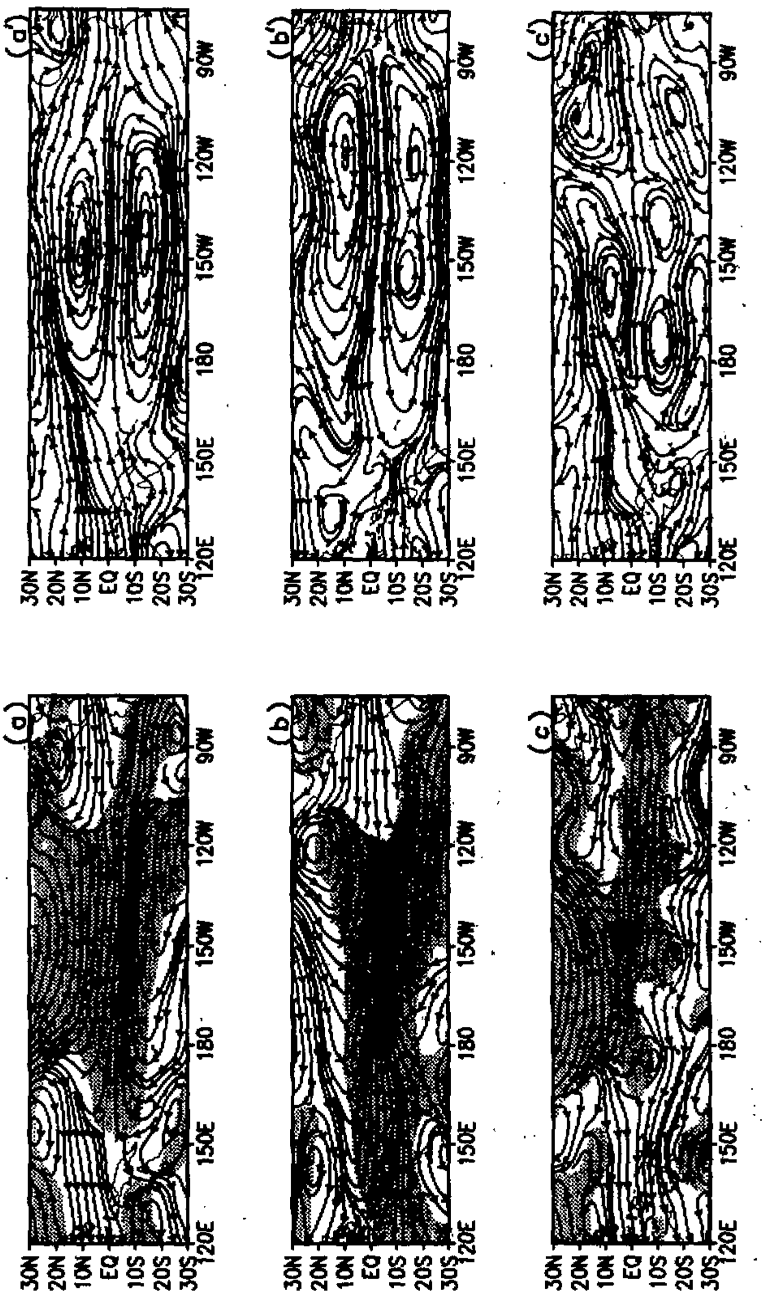

Fig. 6. Same as Fig. 5 but during the prevailing stage of El Nino.

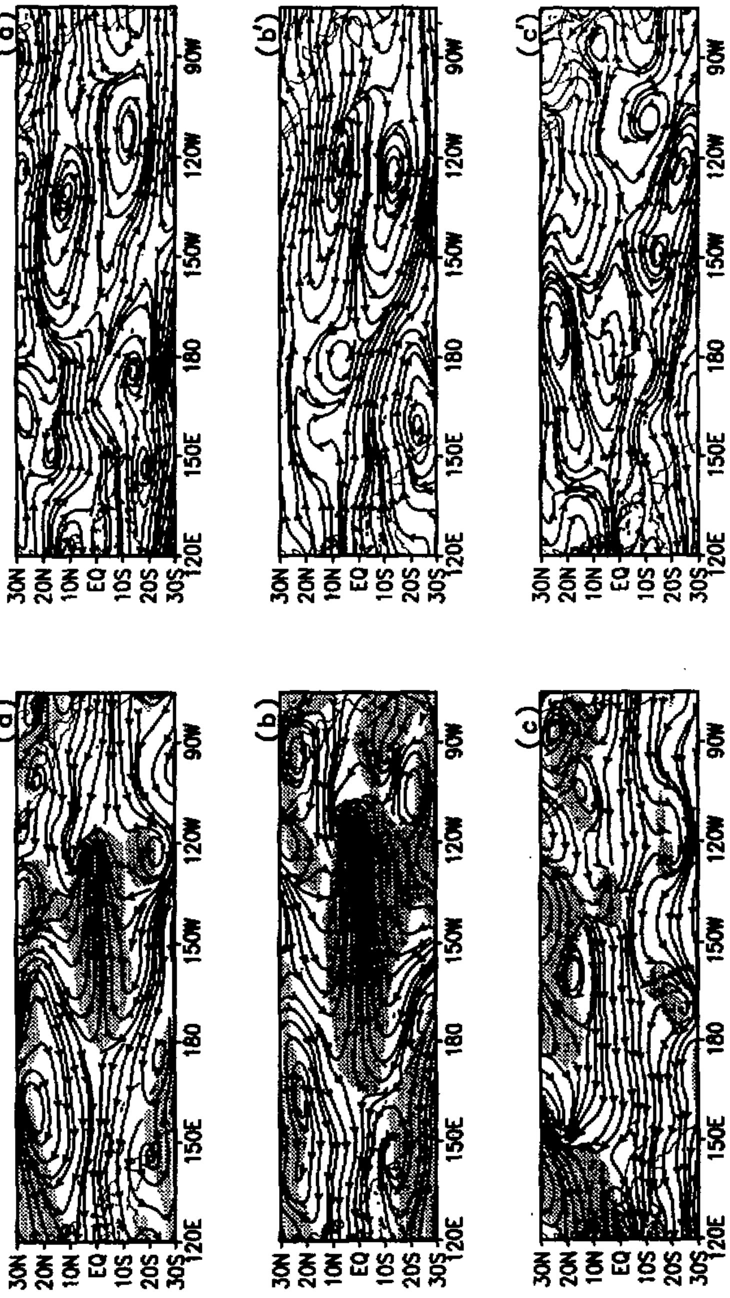

Fig. 7. Same as Fig. 5 but during the later stage of El Nino.

easterly anomalies. The former westerly anomalies merely appear in the area from the date line to 120 ° W. These findings are presented in Fig.7(a), 7(b). At high level (Fig.7(a′), 7(b′)), westerlies get enhanced over the equatorial western Pacific and the two anticyclonic circulations on the either side of equator are obviously weakened and migrate to the eastern Pacific. Difference(TP minus NTP) at low level (see Fig.7(c)) indicates that almost the whole equatorial Pacific is occupied by easterly anomalies. At high level (see Fig.7(c′)), weak easterly anomalies appear over the eastern and western Pacific. Note that the central Pacific is now dominated by westerly anomaly. The above result suggests that the effect of the Tibetan Plateau in this stage is to enhance the easterlies, in other words, it restrains the westerly anomalies.

The evolution of La Nina is roughly opposite to that of El nino. Figures are not shown here. During the earlier period (Jul. 1984; Jul. 1988), easterly anomaly has arisen in central–western tropical Pacific at low level. Two cyclonic circulations are located symmetrically about the equator near 150°W, which results in rather strong westerly anomalies at high level. Subsequently, the low level easterly anomalies along equator is reinforced and moves eastward, so does the high anomalous cyclone at high level. Within the later period, the easterly anomalies along equator remain but its intensity is reduced remarkably. At high level, the two cyclonic circulations make their ways to eastern Pacific with reduced range and intensity. These are some common characteristics in TP and NTP simulations. The difference between anomalies in TP experiment and in NTP experiment keeps positive along or near the equator at low level during La Nina. This leads to a conclusion that the Tibetan Plateau weakens the easterly anomalies in tropics, thus restrains the La Nina developing but promoting its ending.

V. DISCUSSION AND CONCLUSIONS

1. The interannual variability of the wind field over tropical Pacific in TP simulation is in good agreement with that in NTP simulation, particularly in their patterns,and both of them are basically consistent with the observation.This implies that the presence of Tibetan Plateau is not the dominant factor which determines the interannual variability of tropical wind.

2. Vector EOF analysis further shows that the spatial structures of the first mode in TP experiment and that in NTP experiment are similar but the spatial structures of their second mode are significantly different. The time series in the two experiments keep synchronous approximately but their amplitudes are different. This suggests that the influence of the topography on the interannual variability of the tropical wind is reflected by the intensity difference between TP simualtion and NTP simulation.

3. During the earlier period and prevailing period, the Tibetan Plateau strengthens the westerly anomalies along or near the equator at low level as well as the easterly anomalies at high level,thus increases the intensity of El Nino. But for La Nina, its impact is just opposite. Within the later period of El Nino(or La Nina) the effect of orography is to hasten it ending.

Researches in recent years have led to understanding that both anomalies of the external forcings and the internal dynamic processes can result in anomalous variations of atmosphere. Response of atmosphere to the anomalous slowly varying thermal forcings in ocean and ice–cover or snow–cover is an important mechanism of the interannual climate variation (Huang et al. 1992). In the 10–year simulations with and without the Tibetan Plateau, except for sea surface temperature and sea ice which come from observation, the external forcings are all from climatology, including the thermal regime of the Tibetan Plateau itself, such as snow–cover, albedo, and so on. Therefore, besides the internal dynamic processes of atmosphere, sea surface temperature anomalies (SSTA) in tropics, especially SSTA in Pacific are the most fundamental reason for the interannual variability of the tropical wind. It is worthy pointing out that in the above analysis we consider the atmosphere as an isolated system with the prescribed external forcing of ocean. Now we are developing an air–sea coupled model to explore the effect of orography in a coupled system and the results will be published in another paper.

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