NUMERICAL SIMULATION OF THE TROPICAL INTRASEASONAL OSCILLATION AND THE EFFECT OF WARM SST

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ABSTRACT

An atmospheric general circulation model is used in a series of three experiments to simulate the intraseasonal oscillation in the tropical atmosphere. Analyses of the model daily data show that various physical variables, from several different regions, exhibit fluctuations with a spectral peak between 30 and 60 days. This represents a 30—60 day oscillation in the tropical atmosphere and possesses several features which are consistent with observations. These include a horizontal structure dominated by zonal wavenumber 1 and a vertical structure which is predominantly baroclinic.

The effect of warm SST (sea surface temperature) anomalies on the 30—60 day oscillation in the tropical atmosphere is also simulated by prescribing global SST as observed in 1983. This has the effect of weakening the oscillation while at the same time the vertical structure becomes less baroclinic.

The importance of cumulus convection to the propagational characteristics of this oscillation is demonstrated by a comparison of results based on different parameterizations for convection. In one case, where the maximum convection over the Pacific is simulated to be too far east, the simulated 30—60 day oscillation shows evidence of westward propagation. In the second case, where the convection maximum is located near the observed position in the western Pacific, there is more clearly evidence of eastward propagation.

Both results suggest that the location of maximum convection in the Pacific can have an important influence on the strength, structure and propagation of the 30—60 day oscillation.

Key words: numerical experiment, tropical intraseasonal oscillation, cumulus convection, sea surface temperature anomalies (SSTA)

I. INTRODUCTION

Since the tropical intraseasonal (30—60 day) oscillation was first discovered (Madden and Julian 1971; 1972), its structure and propagation have been systematically studied via various methods and different data sets (OLR, wind, etc.). Many studies (Krishnamurti and Subrahmanyam 1982; Murakami et al. 1984; Lau and Chan 1985; Weickmann et al. 1985; Murakami and Nakazawa 1985; and others) have identified certain basic characteristics which can be summarized as follows:

- The intraseasonal oscillation in the tropical atmosphere is dominated by perturbances with zonal wavenumbers 1 and 2, especially wavenumber 1;
- It tends to propagate slowly eastwards;

• The vertical structure tends to be baroclinic with the perturbances typically changing sign between the lower and upper tropospheres.

Several studies have shown that the intraseasonal oscillation tends to be stronger in the southern Asia and western Pacific regions where convection is most active. Analysis of ECMWF data for the period 1980—1988 by Li (1990) showed that a significant amount of kinetic energy associated with the 30—60 day oscillation was also in the equatorial eastern Pacific area, especially in the upper troposphere.

Several general circulation model (GCM) experiments have attempted to simulate the tropical intraseasonal oscillation over recent years (see Hayashi and Golder 1986; 1988; Swinbank et al. 1988; Lau et al. 1988; Park et al. 1990; among others). These experiments have reproduced some of the basic characteristics and have indicated that the structure and eastward propagation are due to the interaction between the large–scale circulation and the latent heat release associated with cumulus convection. But there are evident differences in various GCM experiments and some features of 30—60 day oscillation in the tropical atmosphere need to understand further.

Park et al. (1990) have pointed out that simulated oscillations in GCMs with the same resolution but different physical parameterizations can be very different. This indicates that physical processes, especially the boundary layer moisture processes, are crucial to modelling the intraseasonal oscillation.

The purpose of the present paper is to examine the tropical 30—60 day oscillation simulated by a particular GCM (CSIRO 4) further and to investigate the influence of ENSO on its behaviour. Three experiments have been performed. One of these is referred to as the control experiment (CE) and involves a 2–year integration using climatological monthly SST. The second is a 1–year integration in which observed SST for 1983 has been used. This is referred to as the anomaly experiment (AE). In order to investigate the importance of tropical convection, a third experiment referred to as ME, again used climatological monthly SST but cumulus convection scheme is modified partially.

It should be noted that a kind of low–frequency oscillation, known as the tropical 10—20 day oscillation has been described in several studies (Krishnamurti et al. 1976; Li 1991). This appears as an obvious feature in the numerical experiments and is generally stronger than the 30—60 day oscillation, especially in the summer monsoon region. Details of this particular feature are described in another paper.

The CSIRO 4–level GCM is a primitive equation GCM model with a rhomboid wavenumber 21 spectral representation. The model evolved from a 2–level model which in turn originated from the UCLA / RAND model of Gates et al. (1971). The vertical levels are centered on sigma (σ) levels 0.9, 0.65, 0.35 and 0.1 respectively, where $\sigma = p / p^*$, p is the local pressure and p^* the surface pressure. In this study we analyse the sea level pressure and the fields at both lower ($\sigma = 0.9$) and upper ($\sigma = 0.35$) levels, which approximately corresponding to the 900 and 350 hPa pressure surfaces. Further details can be found in Hunt and Gordon (1989) and Gordon and Hunt (1991).

The analyses described in this paper are based on daily mean fields. Spectral analysis has been carried out on the raw daily data while the analyses of structure and propagation refer to the filtered anomaly fields extracted as follows. Each field was temporally smoothed using a scheme described by Vondrak (1969; 1977). The smoothed values were then subtracted from the raw daily values in order to generate a time series of differences from the seasonal cycle. The intraseasonal oscillation contained in these difference fields was then extracted by the use of a 30—60 day band–pass filter (see Murakami 1979).

II. SPECTRAL FEATURES

Intraseasonal oscillations play a part in long–term weather and short–term climate variability and it is to be expected that numerical weather prediction models and GCMs should be capable of reproducing these features of the atmospheric system. An analysis of any such features within a GCM, as is done here, can assist in understanding the mechanisms associated with intraseasonal oscillations as well as testing the performance of the model and its physical parameterizations. Here we analyse the spectral characteristics of the simulated upper and lower level winds and temperatures, mean sea level pressure and precipitation. We restrict the analysis to the tropical regions between 30°S and 30°N and show power spectra for several selected regions. We deal first with the results from the control experiment CE.

Many studies have shown that activity associated with the 30—60 day oscillation is relatively strong in the monsoon region and the western Pacific area. But, as has been shown, activity is also strong over the equatorial eastern Pacific, especially in the upper troposphere. Consequently, 4 regions where individual power spectra were calculated, have been chosen: northern Australia (NA, 11.1—17.5°S, 123.75—146.25°E), southern Asia (SA, 8.0—17.5°N, 78.75—101.25°E), western Pacific (WP, 8.0—17.5°N, 129.375—151.875°E) and eastern Pacific

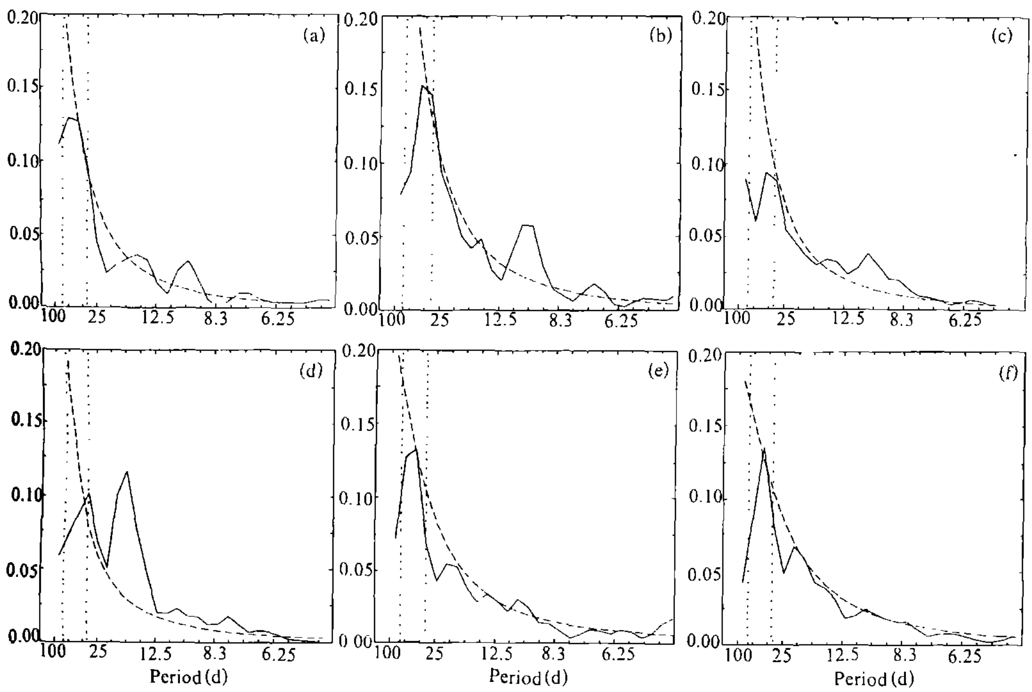

Fig. 1. Power spectra associated with simulated variables for different regions. The dashed line in each case represents the 90% significance level. (a) Mean sea level pressure (SA), (b) mean sea level pressure (NA), (c) upper level zonal wind (WP), (d) upper level zonal wind (NA), (e) mean sea level pressure (EP) and (f) lower level meridional wind (EP).

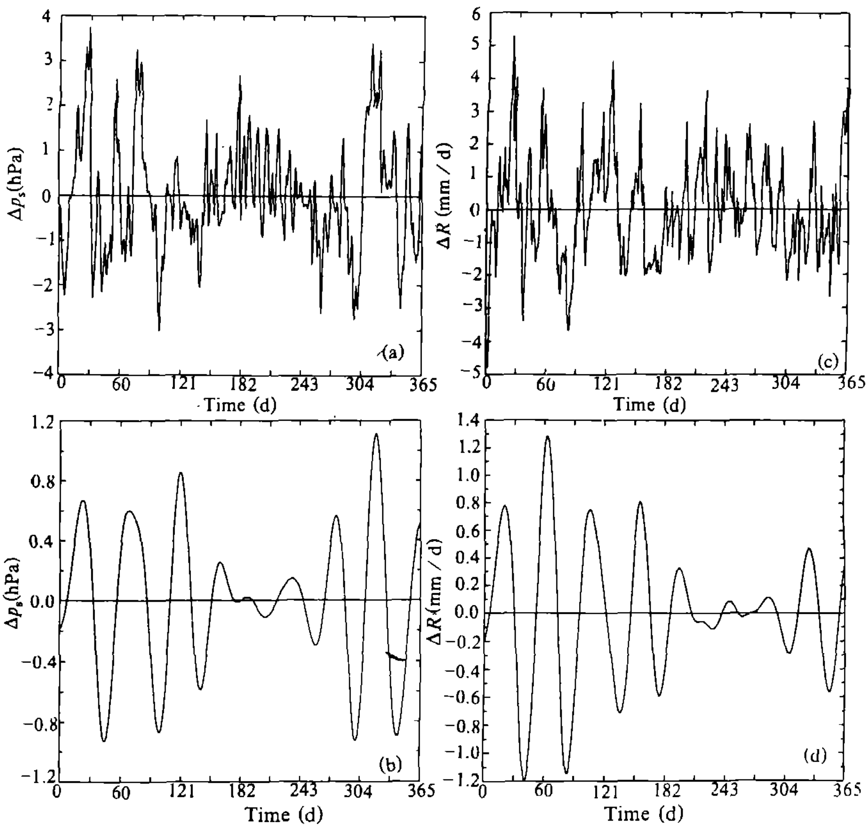

Fig. 2. Time series of (a) simulated daily mean sea level pressure over NA (seasonal cycle removed), (b) after 30—60 day band–pass filtering, (c) simulated daily rainfall over SA (seasonal cycle removed) and (d) after 30—60 day band–pass filtering.

(EP, 8.0—17.5°N, 146.25—123.75°W).

Figure 1 shows the power spectra of simulated mean sea level pressure for SA, NA and EP (Figs.1a, 1b and 1e); the upper level zonal wind for WP and NA (Figs.1c and 1d); and the low level meridional wind for EP (Fig.1f). It can be seen that a peak exists in each spectrum within the 30—60 day period. This indicates that the GCM is capable of simulating a substantial tropical intraseasonal oscillation.

On comparing the various power spectra shown in Fig.1, it can be seen that the 30—60 day oscillation is more evident in the zonal wind and surface pressure fields. It is also clearly indicated in the rainfall data that the oscillation is closely associated with cumulus convection which is the major source of precipitation in the tropics.

Analyses of observational data have shown that the tropical intraseasonal oscillation exhibits a weak variation during the course of a year, being slightly stronger during the northern wintertime. Figures 2a and 2b show the surface pressures for NA both before and after band–pass filtering. Figures 2c and 2d show the same results for the rainfall anomalies for SA. It is clear that the simulated 30—60 day oscillation in the tropics is also stronger during the northern wintertime (November—April).

III. STRUCTURE AND PROPAGATION

Analyses of observational data have clearly shown that tropical 30—60 day oscillation is dominated by zonal wavenumber 1 and that its vertical structure is so baroclinic that the sign is changed from lower to upper atmosphere.

The longitudinal distributions of the 30—60 day band–pass filtered zonal wind at both the upper and lower levels on one day during northern summer are shown in Fig.3. These profiles refer to averages of the simulated zonal wind between 11.1°S and 11.1°N. It can be seen that the upper level profile is characterized by westerlies in the eastern tropics and easterlies in the western tropics. The low level profile exhibits the reverse of this. These profiles demonstrate that the simulated 30—60 day oscillation is dominated by zonal wavenumber 1, and that its vertical structure is basically baroclinic since the anomalies tend to change sign between the levels. This structure feature of the simulated 30—60 day oscillation is also shown in other days (figure omitted). Further evidence of this type of vertical structure is found in the profiles of surface pressure and upper level temperature shown in Fig.4. For example, the regions of relatively high (low) surface pressure correspond to the regions of relatively low (high) temperature.

Figure 5 shows the band–pass filtered wind fields at both the upper and lower levels on one day which is selected wantonly. It can be seen that, in the tropics but away from the equator, the 30—60 day oscillation is stronger in the winter hemisphere than in the summer hemisphere and is associated with extensive vortices. These are features that have been identified by the observational data analysis of Li and Zhou (1991). Figure 5 together with the associated surface pressure field (not shown), indicates that the oscillation along the equator possesses a Kelvin wave–type structure over the Indian Ocean and the western Pacific, and a Rossby wave–type structure over the central and eastern Pacific regions. Some dynamical analyses (Li 1988; Liu

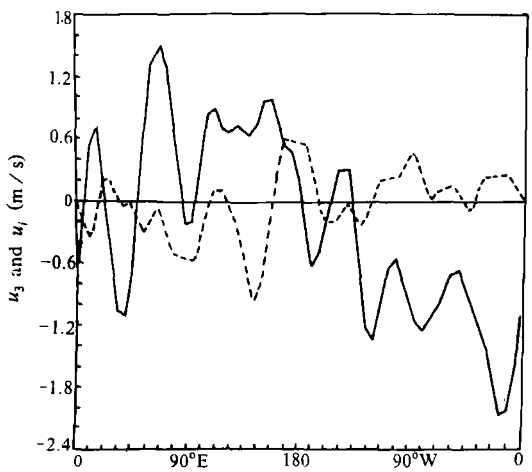

Fig. 3. Longitudinal distributions of the 30—60 day band–pass filtered upper level zonal wind (solid line) and lower level zonal wind (dashed line) averaged between 11.1°S—11.1°N in summer from the control run CE.

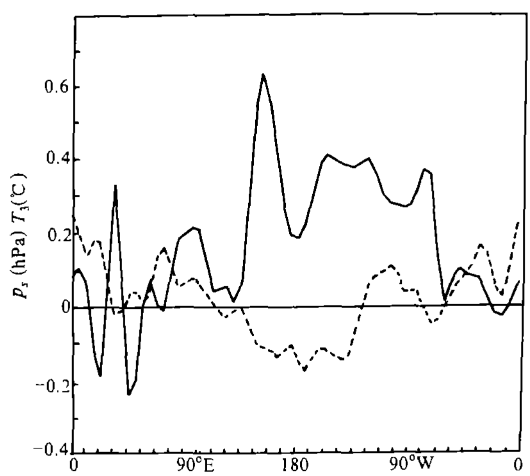

Fig. 4. Longitudinal distributions of the 30—60 day band–pass filtered mean sea level pressure (solid line) and upper level temperature (dashed line) averaged between 11.1°S—11.1°N in summer from the control run CE.

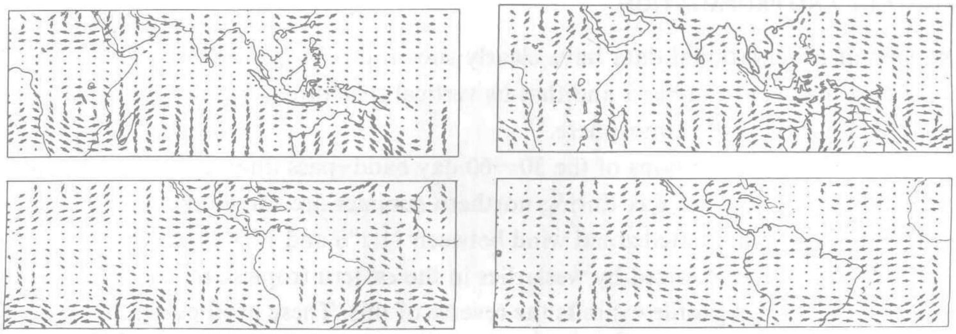

Fig. 5. The 30—60 day band pass–filtered wind fields for (a) upper level and (b) lower level.

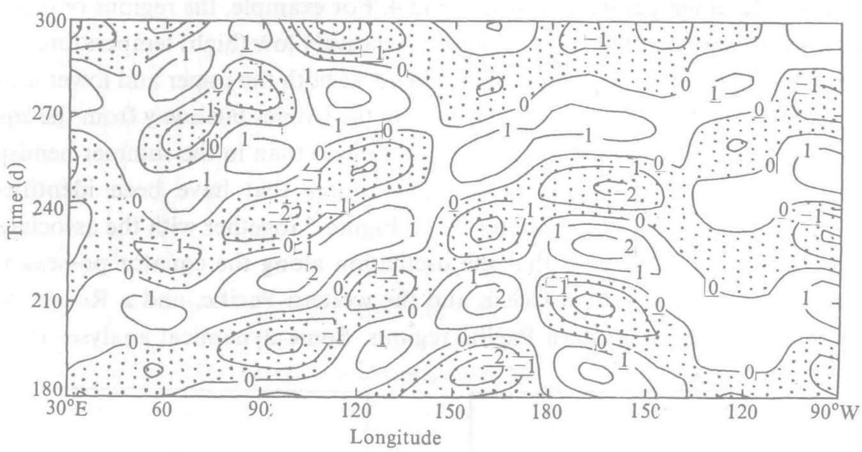

Fig. 6. Hovmoller diagram showing the 30—60 day band–pass filtered upper level zonal wind (day 180—300) from the control run CE.

and Wang 1990) have indicated that the CISK–Kelvin wave and CISK–Rossby wave are all the origin of 30— 60 day oscillation in the tropical atmosphere. The existence of the Kelvin wave–type and Rossby wave–type structures in the simulation experiment shows that the results in GCM simulation are consistent with the dynamic analysis.

Figure 6 shows a Hovmoller diagram of the upper level zonal wind (averaged between 11.1°S and 11.1°N) for the months July to October between 30°E and 90°W. It can be seen that the propagation is eastwards, like observations which show propagating eastwards. Since cumulus convection is believed to be an important factor in the behaviour of the tropical intraseasonal oscillation, in the real atmosphere, strong convection and rainfall in the tropical western Pacific and South Asia regions can excite the 30—60 day oscillation and drive it eastwards. The simulated rainfall distribution is shown in Fig.12a. The eastward propagation consistent with observation seems to result from correct rainfall simulation in the tropics. But the westward propagation can also be seen somewhere in Fig.6. One of reasons may be related to the existence of different tropical wave caused by cumulus convection. The Rossby wave–type structure simulated field over eastern equatorial Pacific will make certain contribution to westward propagation of the oscillation.

IV. INFLUENCES OF ENSO

The relationship between atmospheric intraseasonal oscillations and El Nino may have implications for future climate change. Lau and Peng (1986) proposed that the tropical intraseasonal oscillation can initiate an El Nino event through the coupling interaction between the atmosphere and oceans, i.e. westerly wind bursts in the western Pacific associated with the propagation of a 30—60 day oscillation may excite an oceanic Kelvin wave which eventually depresses the thermocline in the eastern Pacific, and leads to anomalously warm SST. Li and Zhou (1994) have shown that the kinetic energy associated with the 30—60 day oscillation tends to be strongest over the equatorial central–western Pacific prior to the occurrence of an El Nino event. Figure 7 shows the interannual variation of the 200 hPa kinetic energy associated with 30—60 day oscillation over the tropical western Pacific (10°S—10°N, 140—160°E) as calculated from ECMWF data. It can be seen that kinetic energy maxima occurred prior to 1982—1983 and 1986—1987 El Nino events, suggesting that the oscillation may be a factor in triggering these events. It is also apparent that the kinetic energy of the 30—60 day oscillation in the tropics is relatively small during the El Nino events. This may mean that the oscillation might be weakened by El Nino event.

As a means of investigating the effect of an El Nino event on the simulated 30—60 day oscillation, experiment AE was performed in which the relatively warm SST of 1983 was prescribed for the 1–year integration. The longitudinal distributions of upper level kinetic energy associated with the oscillation from both CE and AE are shown in Figs.8a and 8b. The kinetic energy is about 25—30% less for AE, particularly over the western Pacific, suggesting that the warmer SST may indeed have suppressed activity. In general, during an El Nino event, the kinetic energy of 30—60 day oscillation in the tropical atmosphere is also reduced as shown in Fig.7. This further shows that the simulated activity associated with the 30—60 day oscillation is consistent with observations of real behaviour. However, it should be noted that some theoretical studies (e.g. Lau and Peng 1987; Wang 1988) suggest that warm SST should be favourable for increasing the activity of the oscillation. Therefore, it appears that further study of the mechanism and the reasons why the tropical intraseasonal oscillation is weakened during an El Nino

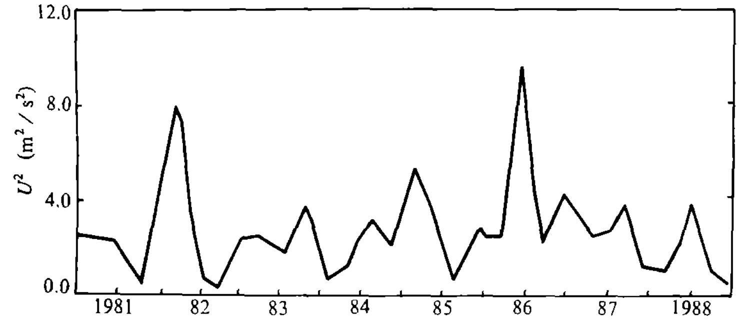

Fig. 7. Observed interannual variation of kinetic energy (K) of the 30—60 day oscillation at 200 hPa in the tropical atmosphere over the equatorial western Pacific (10°S—10°N, 140—160°E) (calculated from ECMWF data).

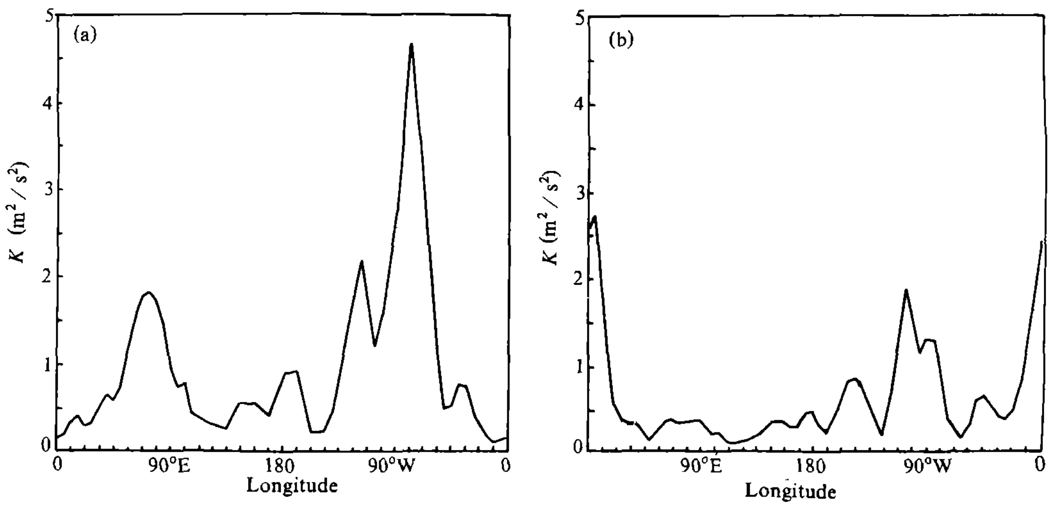

Fig. 8. The longitudinal distribution of kinetic energy (K) associated with the simulated intraseasonal oscillation of the upper level wind field in August.

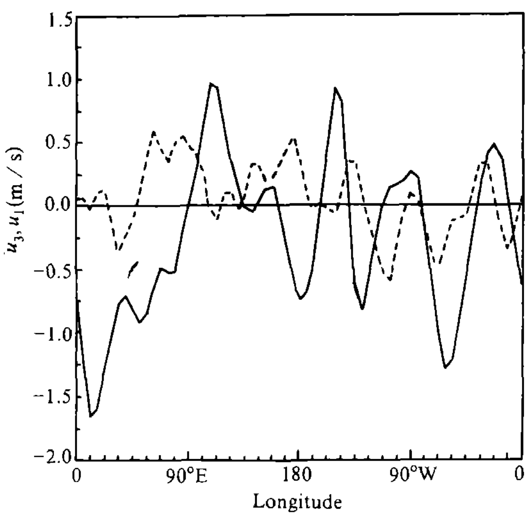

Fig. 9. As in Fig.3, but for the anomaly experiment AE.

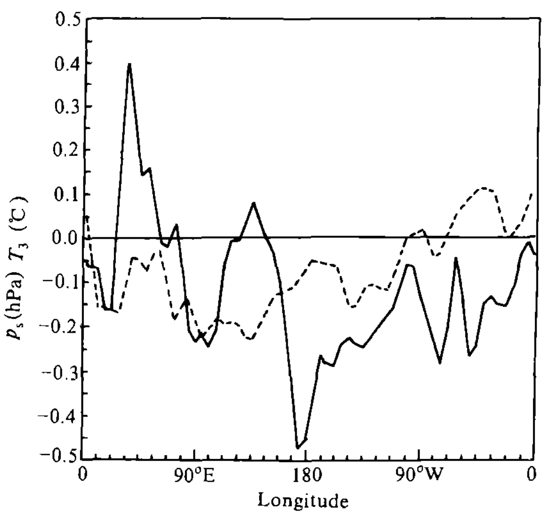

Fig. 10. As in Fig.4, but for the anomaly experiment AE.

event, is very necessary. Recently, a dynamical analysis has shown that the SST anomalies, as El Nino event, will prevent the 30—60 day mode in the tropical atmosphere (Li and Li 1993).

Not only is activity weakened in the El Nino–like (AE) but the vertical structure is also changed. Figure 9 shows the longitudinal distributions of the band–pass filtered upper and lower level zonal winds, and indicates that, different from in Fig.3, the structure is more barotropic. Similarly, the distributions of surface pressure and upper level temperature shown in Fig.10, clearly suggest a barotropic structure. Other results from AE (not shown) indicate that the vertical structure tends to become predominantly barotropic in conjunction with the warmer SST in the eastern Pacific.

Based on the ECMWF data, the structures of tropical intraseasonal oscillation in summer for 1981 and 1982 are analyzed, and respectively shown in Fig.11. The results represented that the vertical structure of tropical intraseasonal oscillation in the summer of 1982 (El Nino year) has less baroclinic features than in the summer of 1981 (non El Nino year). Therefore, the present simulation has similar results with observations and shows the El Nino event will cause the vertical structure of tropical intraseasonal oscillation to be much barotropic.

V. IMPORTANCE OF CUMULUS CONVECTION

Dynamical studies have indicated that cumulus convection feedback is fundamental to exciting the 30—60 day atmospheric oscillation in the tropics (Li 1985; Lau and Peng 1987). In order to study the effect of convection heating on the tropical 30—60 day oscillation in GCM, a modified experiment is completed.

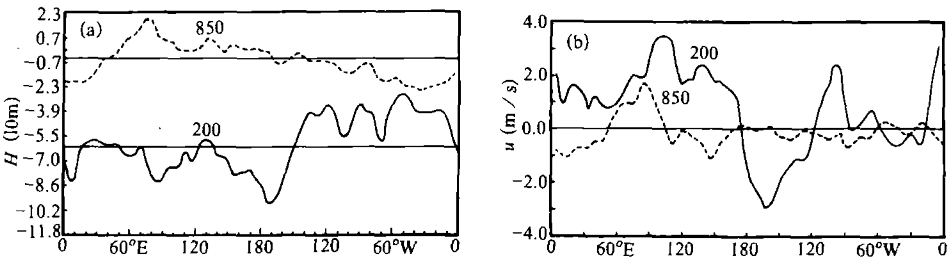

Fig. 11. The vertical structure of intraseasonal oscillation in the tropical atmosphere analyzed based on ECMWF data: (a) 1981 summer and (b) 1982 summer.

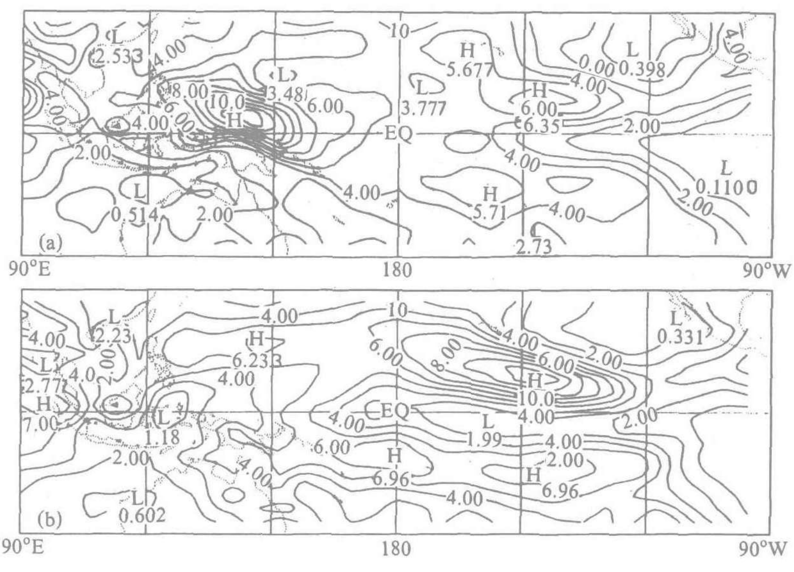

Fig. 12. The simulated annually averaged precipitation rate (mm / d) over the tropical Pacific and eastern Indian Ocean (a) from CE and (b) from ME.

A third experiment, referred to as ME, was performed in which the parameterization of cumulus convection was changed, resulting in a tropical rainfall distribution more different from observation. Figure 12a shows the annual averaged mean daily precipitation throughout the tropical Pacific from the original control run. It can be seen that the rainfall, dominated by convective processes, has a maximum in the western equatorial Pacific region and it is consistent with the observation. Figure 12b shows the distribution corresponding to a modified cumulus convection scheme and has an unrealistic maximum rainfall in the eastern Pacific. Corresponding to this rainfall distribution, the upward branch of Walker circulation is changed in the location.

Figure 13 shows a Hovmoller diagram of the upper level zonal wind from ME and can be compared to Fig.6. It can be seen that the propagation is predominantly westwards, especially in the central–western Pacific and the Indian Ocean regions. This result provides evidence that cumulus convection has an important effect on the behaviour of the tropical 30—60 day oscillation and that it must be carefully parameterized in GCMs. Apart from improving the basic control climatology in the tropics, a convection scheme which also enables the propagational features of the 30—60 day oscillation to be better simulated, will obviously improve any simulations of climate change.

VI. CONCLUSIONS

The intraseasonal oscillation is an important feature of the tropical atmosphere and, ideally, should be simulated by any GCM. This is particularly relevant for both long–term weather prediction and climatic change experiments. Numerical experiments as described here can provide an effective means of examining features of the intraseasonal oscillation in the tropical atmosphere, and also provide an important test of model performance.

Analyses of the results of three numerical experiments (CE, ME and AE), have shown that basic features of the tropical 30—60 day oscillation can be simulated with a particular GCM, CSIRO 4. The power spectra of various physical variables (surface pressure, wind, temperature and precipitation) from several tropical regions all reveal peaks between 30 and 60 days. This

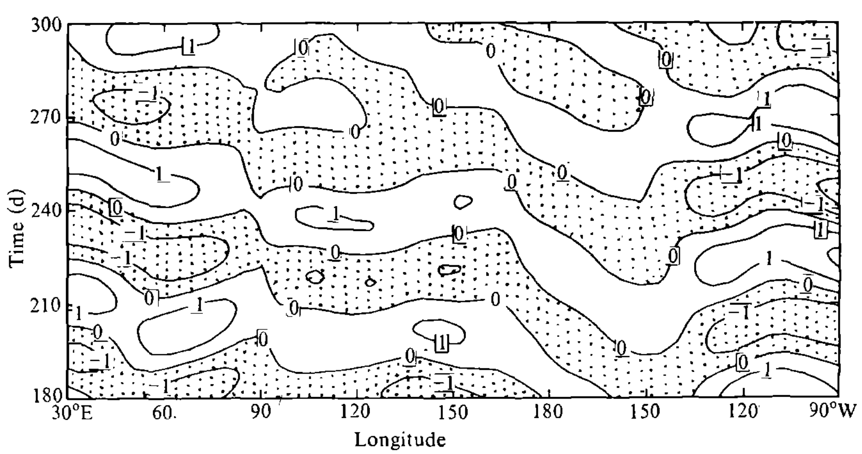

Fig. 13. As in Fig.6, but for the modified convection scheme experiment ME.

shows that the tropical 30—60 day oscillation is simulated by the model and it is consistent with observations, and widespread. Of more importance is the fact that the simulated 30—60 day atmospheric oscillation in the tropics possesses a structure which is also consistent with observations. Its horizontal structure is dominated by zonal wavenumber 1 in the tropical atmosphere, and the vertical structure is basically baroclinic, as evidenced by the change in sign of the anomalies between the lower and upper levels.

Cumulus convection feedback has been considered an important mechanism in exciting the 30—60 day oscillation in the tropical atmosphere. A comparison between the results of two experiments, each involving different parameterizations for cumulus convection, reinforces this proposition. In the modified experiment ME, it not only changed the tropical rainfall distribution, but also resulted in a changed simulation of the 30—60 day oscillation propagation. In the real atmosphere, the eastward propagation of tropical 30—60 day oscillation from the western Pacific and the Indian Ocean area is possibly related to the strong large–scale convective activity (and associated heating) occurring there.

Another interesting result refers to the influence of warm SST (or El Nino events) on the 30—60 day oscillation in the tropical atmosphere. In a simulation in which warm SST was prescribed, the kinetic energy of the simulated oscillation was clearly reduced. At the same time, the vertical structure tended to become more barotropic. These results are essentially diagnostic since they involve analysis of just a few basic fields. A more detailed study awaits the analysis of the important heating sources and sinks and a complete explanation of the results in terms of dynamical theory will require further study. Even so, it is possible that the location and the pattern of external forcing (represented by the SST anomalies) can affect the structure of the excited low–frequency mode in the tropical atmosphere.

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