Dynamics of Multi-Scale Interactions Relevant to ENSO

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1. Introduction.

This study is an extension of the work of Lau and Peng (1987, hereafter referred to as LP) on the origin of intraseasonal oscillations (ISO, also known as the 30-60 day oscillation) in the tropical atmosphere. In this note we present some preliminary results of numerical experiments focusing on the mechanism of multi-scale interaction, in particular those related to origin of ISO, supercloud cluster (SCC), westerly wind burst (WWB) in the western Pacific region (cf. Nakazawa, 1988; Keen, 1987; Nitta and Motoki, 1988; Lau and Chan, 1988). The relationship between SCC and ISO has been identified previously in Hayashi and Sumi (1986) and LP. Here it will be shown that WWB can be linked to the same family of multi-scale processes that govern SCC and ISO and ENSO over the western Pacific.

2. Model description.

The model used in this study is similar to that used LP - 5 vertical level spectral model with rhomboidal truncation to 15 wavenumbers. A semi-implicit time differencing scheme with Robert-Asselin type averaging is used in the integration. This provides strong damping of gravity waves in the model. The present version includes nonlinearity in the advective terms which are computed on a Gaussian grid at a resolution of approximately 7.5 degree by 4.5 degree. The vertical heating profile used has maximum heating between 500 and 700 mb (see Sui and Lau ,1989, for further details). The atmosphere has no mean motion and the horizontal mean temperatures are given by the observed equatorial zonal mean temperatures, with fixed specific humidity.

3. Mobile wave-CISK modes and SCC.

It is clear from LP and Sui and Lau (1989) that the propagation speed and vertical structure of the 30-60 day oscillation is sensitive to the level of maximum heating in the troposphere. The vertical zonal wind distribution of the mobile wave-CISK mode for different vertical heating distributions is examined in the section. Three cases are considered with a similar heating profile except having.

I Maximum heating near 300 mb,
II Maximum heating between 500 and 700 mb, and
III Heating profile as in Case II and evaporation and sensible heating proportional to the 900 mb wind according to a bulk aerodynamic formulation. All the sensible heating is assumed to be realized in the lowest model layer (1000-900 mb; see Sui and Lau, 1988, for details).

When the heating is concentrated in the upper troposphere (case I, Fig. 1a), the vertical scale of the disturbance is large, the westward tilt with height extend throughout the troposphere. The westerly wind is maximum in the upper troposphere and to the east of the heat source. At the surface, the westerly (Rossby) is slightly stronger than the easterly (Kelvin) inflow towards the heat source. The eastward propagation speed for

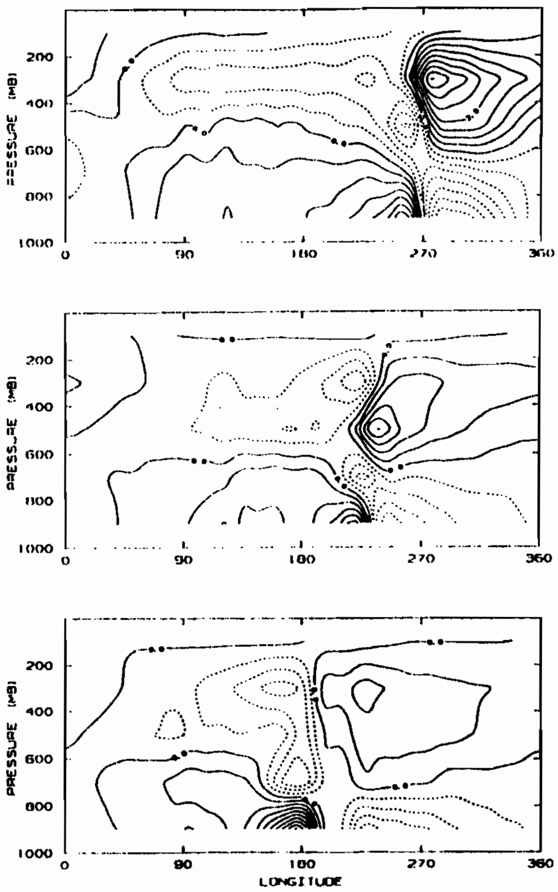

FIG.1. Vertical cross-section of zonal wind mobile wave-CISK mode for different heating profiles. a) maximum heating near 300 mb. b) maximum heating between 500 and 700 mb and c) same as in b) but include surface heating.

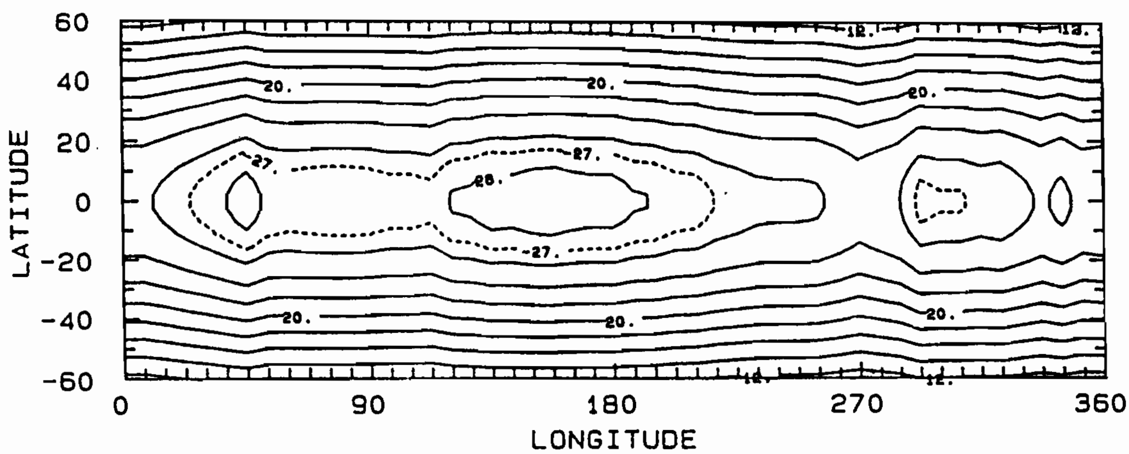

FIG.2. Spatial variation of SST used for the westerly wind burst experiment.

this mode is about 23 ms^{-1} (20 day oscillation). When the heating maximum is between 700 and 500 mb (case II, Fig. 1b,) the vertical scale is reduced and the westward tilt with height is limited to the lower troposphere. At the surface, the westerlies flow is stronger than the easterlies, suggesting the increasing importance of Rossby waves. This mode propagates with an eastward phase speed of about 9 ms^{-1} (50 day oscillation). When latent and sensible heat flux is included, the vertical distribution of the SCC changes drastically (case III, Fig. 1c). First, the vertical phase tilt is reduced and the zonal wind maximum is further away from the convective center. Second, the east-west asymmetry of the surface zonal winds become very pronounced. Strong surface westerlies are found in a shallow layer to the west of the convective center and the easterlies are considerably weaker. The eastward propagation speed is about 13 ms^{-1} (36 day oscillation). Evaporation provided additional source of moisture for deep convection through wave-CISK. More importantly, it appears that sensible heating is responsible for the presence of the shallow layer of westerlies in the wake of the eastward propagating SCC. Thus, low tropospheric heating and in particular, surface heating may be important in leading to an asymmetric low level westerly wind in the model. This may have important implication on the connection between SCC and the westerly wind burst phenomenon in reality.

4. Westerly wind burst experiment

The effect of asymmetric SST and surface heating on the structure and propagation of mobile wave-CISK modes have been examined in detail in Sui and Lau (1988). The following is a discussion of an experiment focusing on the surface wind fluctuation in the model which we tentatively identify with WWB. In the experiment, a bogus low level convergence center is imposed on the equator initially. An eastward propagating precipitation and circulation complex resembling SCC is formed as a result of mobile-wave CISK. The equilibrium SCC structure shown in figure 1c is allowed to propagate through a zonally varying SST distribution as shown in figure 2 which mimics the climatological SST distribution along the equator. Here, the effect of the varying SST is to produce a varying amount moisture available for moist convection through evaporation as well as to provide different amount of surface heating as a function of the air-sea temperature difference and wind. The detailed evolution of the SCC vertical structure and phase speed as a function of the longitude is similar to that shown in Sui and Lau (1988) and will not be repeated here. Only features deemed to be related to SCC and WWB are highlithed in the following.

Figure 3a shows the longitude-time section of precipitation for the first 96 days of the integration. As the SCC (maximum precipitation region) propagates over the warm water, it undergoes vigorous dynamical adjustment because of the changing moisture and stability in the overlying atmosphere. This is manifested in the eastward organization of the SCC by Kelvin waves and the westward propagation of convective elements associated with Rossby waves. The SCC disappears over the eastern Pacific, due to the inhibition of deep convection over the cold water. It revives somewhat over the warm and moist Amazon region, before disappearing over the Atlantic and finally recovered over the Indian Ocean/Western Pacific region. The cycle appears to be repeated indefinitely about every 36 days. Although the SCC appears to turn on and off at different longitudes, it appears to follow more or less the same longitude-time path indicating a somewhat constant underlying phase speed. This is because the large scale zonal winds in the lower troposphere maintained both by convection and surface heating are basically continuous over the entire journey around the equator (Fig. 3b). The wavy appearance of the surface westerlies behind and the relatively steady easterlies ahead of the mobile heat source is quite apparent. It is also noticed that this east-west asymmetry is most pronounced over the warm part of the ocean between 90° and 180° longitude.

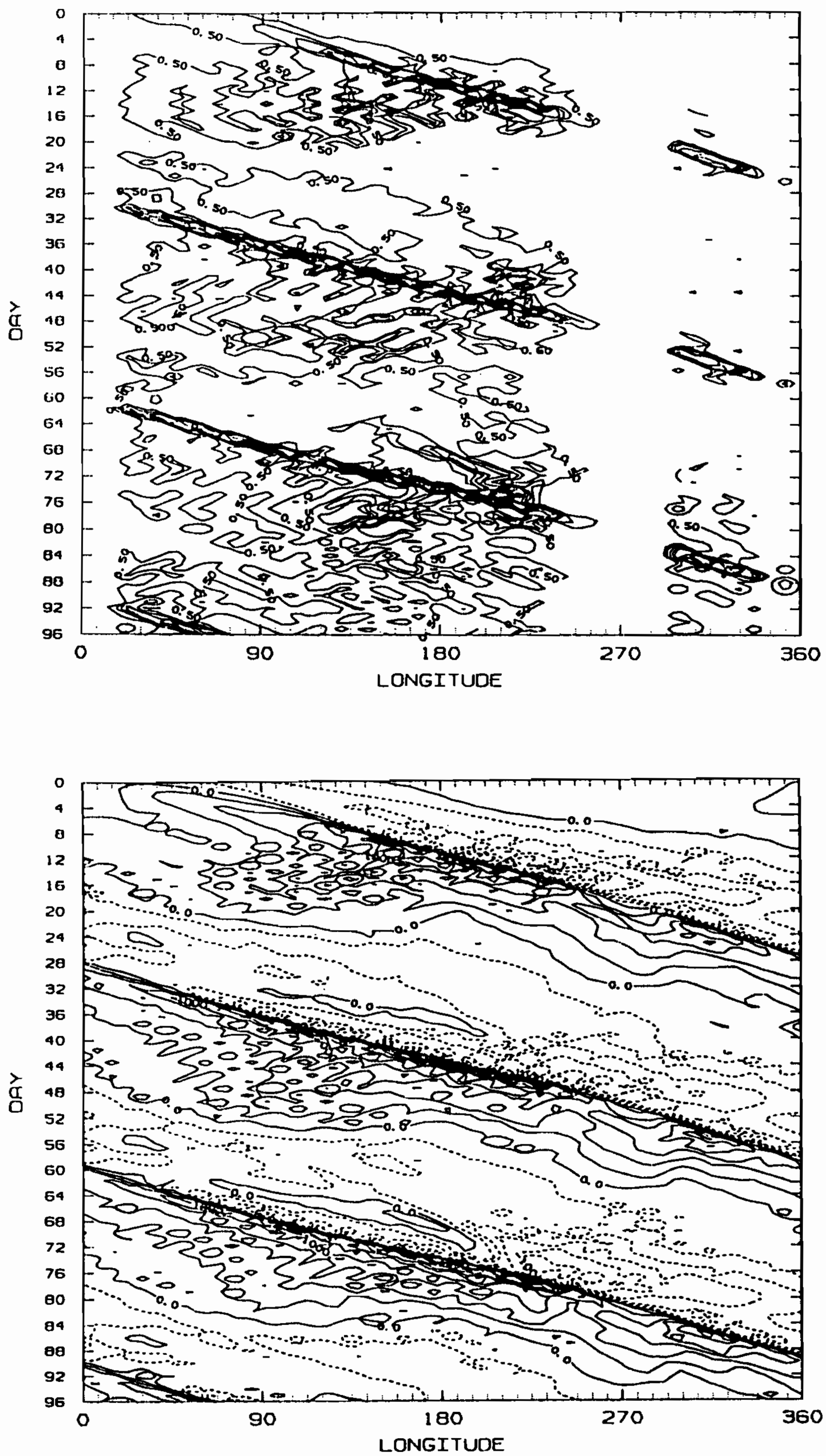

FIG.3. Time-longitude section of (a:top) precipitation (mm.day^{-1}) and (b:bottom) 900 mb wind (ms^{-1}) associated with the model SCC.

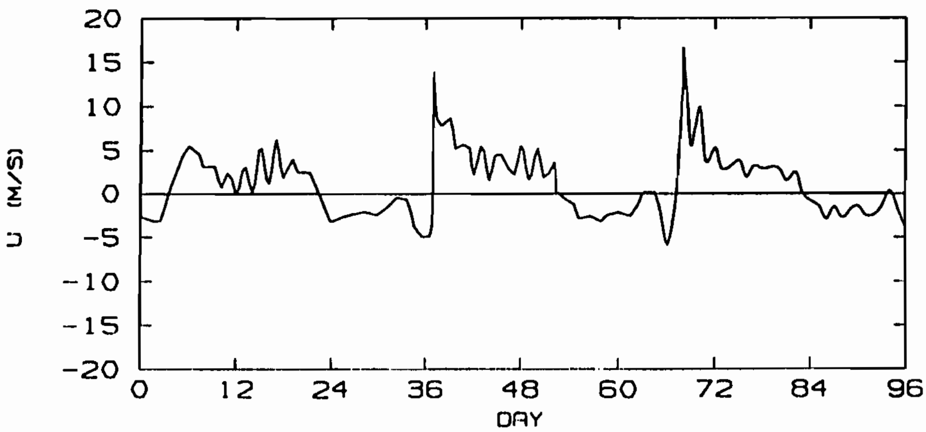

FIG.4. Time series of 900 mb zonal wind at 160°E showing the strong asymmetry between the westerly and the easterly phase of the model 30-60 day oscillation.

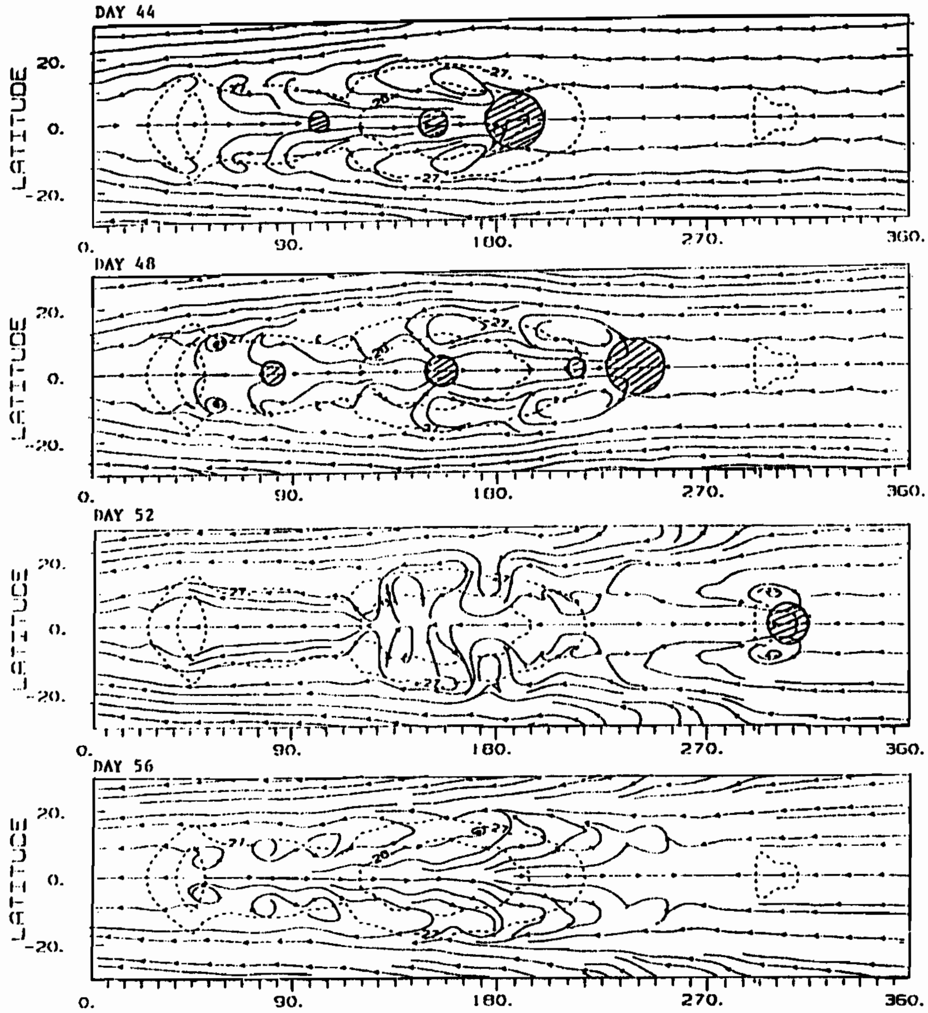

FIG.5. Horizontal distribution of streamline in relation to SCC precipitation centers (hatched circles), and the warm water region (SST >27°C, dotted contour), at selected dates.

Figure 4 shows the time series of 900 mb zonal wind at a fixed point around 160°E. The strong asymmetry and the front-like reversal between the westerly and the easterly component of the zonal wind is clearly seen. The easterly component is quite steady but the westerly component is very spiky and contains many high frequency fluctuations. This is related to the strong east-west asymmetry of the intrinsic structure of the SCC noted in figure 1c and the global picture described in figures 3a and 3b. As the SCC propagates eastward, an observer over the warm ocean will first experience the steady surface easterlies due to Kelvin waves. The passage of the convective center marks the abrupts shift from easterlies to westerlies. This is followed by high frequency zonal wind fluctuation in the westerly phase due to Rossby waves shedded off the main heat source as it propagates further to the east. The above situation is repeated in 36-day cycles in the model. For each cycle, the westerly phase of the oscillation lasts about 20-25 days and the easterly phase about 10-15 days. The spatial distribution of 900 mb wind in relation to the location of SCC and large scale SST is shown in figure 5. While the main SCC center propagates eastward, secondary centers move westward. Each of the centers is associated with a Rossby wave couplet or double cyclone as they propagate away from the warm water pool. As a result, the westerlies expand zonally with the major convection confined to the eastern terminus of the region of westerlies. There is a remarkable contrast between their steady easterly wind east of the SCC and the wavy circulation patern in the region of the westerlies over the warm pool.

5. Dynamical origin of westerly wind burst

Based on the above results, it may be concluded that the sudden occurrence of westerly wind over the open warm water region (equatorial western and central Pacific) associated with WWB may be due to:

(a) a direct response of the lower tropospheric wind to the passage of the eastward propagating main SCC heat source associated with the 30-60 day oscillation and/or
(b) zonal wind fluctuations on the equatorial side of the twin cyclonic vortices emanating from the main heat source.
(c) The eastward propagating SCC which is at the eastern extreme of the region of westerlies is directly related to strong convection while those associated with Rossby waves may or may not be accompanied by strong convection. This may be the reason why the most intense precipitation is often found near the eastern terminus of the westerlies and that some westerlies outbursts are not related *locally* to convection (Keen, 1987).
(d) The rapid expansion of the region of surface westerly is the result of the SCC complex extending both eastward (by Kelvin waves) and westward (by Rossby waves) as the large scale circulation and the latent heating fields undergo mutual adjustment.

A summary of the above features in illustrated schematically in figure 6.

6. Relevance to ENSO

A recent study by Lau and Shen (1988) suggests that a new set of unstable coupled ocean-atmosphere modes arises as a result of including the physics of the 30-60 day oscillation in the atmospheric model. Figures 7a and 7b show the dispersion relationship of an unstable coupled mode as a function of the mean SST. This unstable mode is due to the interaction of zonal SST advection and atmospheric zonal wind fluctuations such as the multi-scale processes described in the preceding sections. As SST increases, the atmospheric disturbances move slower as indicated by the decreasing

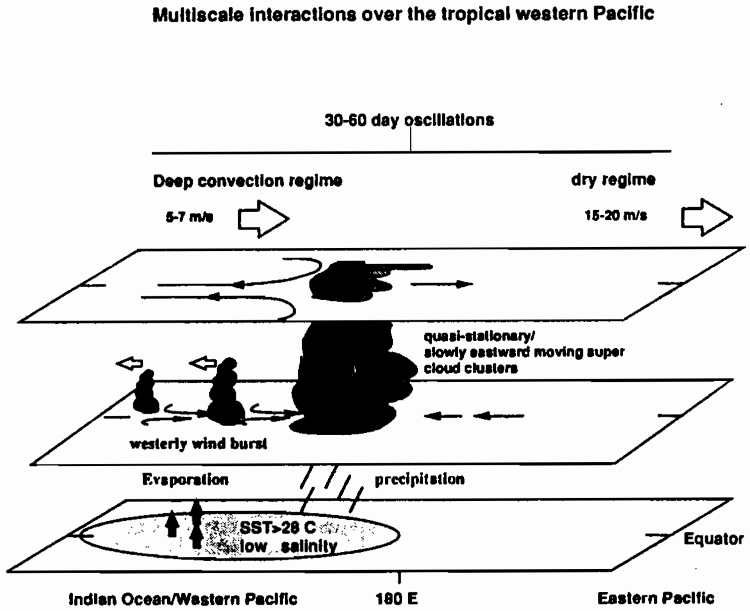

FIG.6. Schematic showing the hierarchical structure of intraseasonal oscillation, westerly wind burst and super cloud cluster over the tropical Pacific as inferred from observations and model simulations.

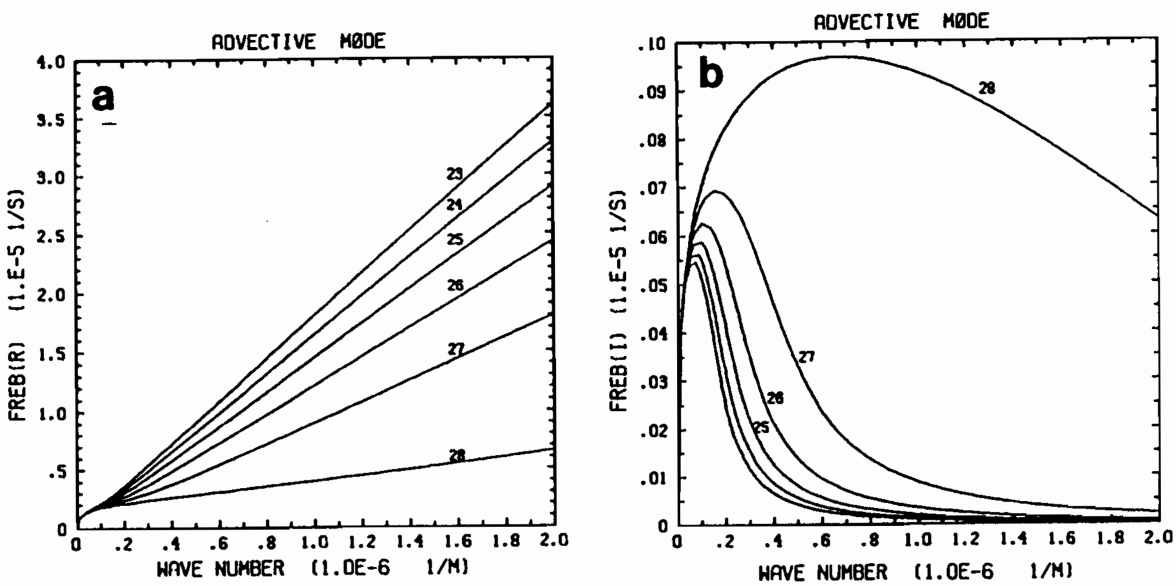

FIG.7. Dispersion relationship for unstable coupled moist ocean-atmosphere modes as a function of SST for (a) real part and (b) imaginary part of the frequency. The atmospheric model contains explicit moist physics. Only zonal SST advection is included in the ocean model (adapted from Lau and Shen, 1988).

slope of the dispersion curves (Fig.7a). More importantly, as the mean SST increases, the coupled instability increases drastically between 27° to 28° C as indicated by the large increase in the imaginary frequency between these two SSTs (Fig.7b). This critical range of SST is a function of the unstable or marginally stable stratification of the tropical western Pacific and the nonlinearity in the Clausius-Claperyron relationship governing saturated moisture and temperature (see Lau and Shen ,1988, for details). The strong dependence of the stability on SST alone may be an over-simplification of the model. But the possibility that the entire hierarchy of motions depicted in figure 6 may be dynamically unstable when coupled to the ocean is a crucial factor that need to be taken into account in our understanding of the onset mechanisms for ENSO.

The results presented here is consistent with the view that the ISO, WWB may be instrumental in triggering the onset of ENSO (Lau, 1985; Lau and Chan, 1988). It is important to note that ISO, WWB, double vortices or even typhoon that have been invoked as causes for ENSO onset should not be regarded as separate or single phenomenon that by itself will cause ENSO. The key to the triggering is the strengthening of the equatorial surface westerly wind. Features like double vortices may occur as necessary accompaniments to the increase in surface westerly wind. Typhoons may be further development of these vortices away from the equator. At best, they serve as signals of strong westerly wind that are occurring in the equatorial region but are themselves not germane to the ENSO triggering process. An important consideration from the present study is that the surface westerlies during ENSO onset occur episodically and with a high degree of variability. Interactions among the intermediate to high frequency components such as ISO, SCC and WWB may play key roles in the onset of ENSO.

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