The Role of Zonal Advection Feedback in Phase Transition and Growth of ENSO in the Cane-Zebiak Model

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Abstract

The turnabout and growth mechanisms of the ENSO are diagnostically studied by analyzing the SST budget of the Cane-Zebiak model. The SST change rates, which are directly linked to the phase transition and growth of the ENSO, are attributed to two processes: the anomalous vertical advection of subsurface temperature by the mean upwelling (thermocline feedback), and the zonal advection of the climatological mean SST by the anomalous zonal current (zonal advection feedback). The contributions to the phase transition, and growth of the ENSO, can be systematically separated by decomposing the equatorial thermocline depth anomaly, and zonal current anomaly into their zonal mean and zonal contrast fields. It is found that the thermocline feedback, associated with the zonal mean thermocline depth anomaly, and the zonal advection feedback by the equatorial zonal mean zonal current anomaly are responsible for the phase transition of the ENSO. Those associated with zonal contrast fields are responsible for the growth of the ENSO. The two processes in the SST change contribute to the phase transition and growth of the ENSO in an almost equally significant manner. They are closely related, as a result of the geostrophic balance between the meridional gradient of the thermocline depth and the zonal current. These findings suggest that the conceptual understanding of the ENSO in the Cane-Zebiak model, should include both of these two processes.

1. Introduction

As postulated by Bjerknes (1969), the El Niño-Southern Oscillation (ENSO) has been referred to as a Pacific basin-wide interannual variation of the tropical ocean and atmosphere interactions. Consid-

erable research efforts have been devoted since then to a better understanding, and to the prediction of the ENSO (Reviews in *J. Geophys. Res.* edited by Rothstein *et al.*, 1998). A great deal of work has been done regarding the mechanism of the growth and phase transition of the ENSO (*e.g.*, Wyrski, 1985; Yamagata, 1985; Hirst, 1986, 1988; Suarez and Schopf, 1988; Battisti and Hirst, 1989; Wakata and Sarachik, 1991; Jin and Neelin, 1993; Jin, 1996, 1997a, b; Li, 1997; An and Kang, 1998; Wang *et al.*, 1999; Jin and An, 1999).

The delayed oscillator theory (Schopf and Suarez,

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1988; Suarez and Schopf, 1988; Battisti and Hirst, 1989), and recently the recharge oscillator theory (Jin, 1996, 1997a, b; Li, 1997), have been proposed to describe the ENSO transition and growth mechanisms on the basis of the non-equilibrium adjustment processes of the ocean. They suggested that the SST change linked to the phase transition and the growth of the ENSO, would be mostly accomplished by the anomalous vertical advection of the subsurface temperature by the mean upwelling associated with the thermocline depth anomaly. This process is referred to as thermocline feedback. Picaut and his colleagues (Picaut and Delcroix, 1995; Picaut *et al.*, 1996, 1997; Delcroix and Picaut, 1998) through the observational work, stressed the importance of the advection of the mean SST by anomalous zonal current in the phase transition and growth of the ENSO. This process is referred to as zonal advection feedback. A similar controversy between the thermocline feedback in Philander *et al.* (1984), and the zonal advection feedback in Gill (1985), had been reconciled by Hirst (1986) within the framework of coupled instability. Recently Jin and An (1999), within the framework of the recharge oscillator model, proposed a unification of these two competing theories by considering these two feedbacks.

In the present study the conjunctive mechanism of the thermocline and zonal advection feedbacks are investigated by using a diagnostic analysis method of the SST budget in the Cane and Zebiak model (Cane and Zebiak, 1985; hereafter the CZ model). This method allows a clear separation of the processes of the transition, and instability mechanism, from the standpoint of the SST budget. It gives a clear quantitative way to obtain the relative importance of the different contributing processes for the instability and the transition, both in the model and the observed data.

This paper is organized as follows. In Section 2, we briefly describe the model and introduce the statistical method in order to show a general cyclic feature of the ENSO. Section 3 discusses, by using the partial flux form, the evolution of the thermal advection associated with the ENSO. In Section 4, we address the transition and instability mechanisms by separating the SST budget according to their role as either the transition, or the instability mechanism. In Section 5, summary and discussion are provided.

2. Model and analysis method

The CZ model is used in the present study. The atmosphere in the CZ model is expressed in terms of a steady-state, linear shallow water equation in an equatorial beta-plane. The ocean model is composed of the fixed-depth surface mixed layer determining the SST anomalies and the upper layer in which the thermocline depth and currents are de-

termined. They are described by a linear shallow water equation. SST is determined by the horizontal advective in the mixed layer, vertical advection by the upwelling, and Newtonian cooling. The basic states are prescribed, with the observed climatological monthly mean. In order to get a standard-run data, the CZ model was initially perturbed by a prescribed zonal wind for the first four months, and then allowed to run freely for 100 years. The result after 20 years of integration is used in this study. The produced data resolutions are 5.625° by 2° .

In order to depict the evaluation of the ENSO in the CZ model, we will show a lag covariance between the normalized NINO3 (5°N – 5°S , 150°W – 90°W) SST anomaly, and the SST tendencies derived from various advection terms. Units of the resultant lag covariance are the dimensional quantities, *i.e.* SST change rate to the time (in this study, $^\circ\text{C}/\text{month}$).

Although the SST pattern associated with the ENSO is the large scale covering almost the whole tropical Pacific, it is hard to define the meridional scale of the SST in order to favor generation of the interannual oscillation in some sense. We can define the meridional scale based on the numerical results of the CZ model. By testing the CZ model sensitivities to change in the meridional scale of the zonal bands in which the SST tendency is calculated, it is verified that the oscillation is possible if the zonal band of the SST tendency is at least 5°S – 5°N . If we choose the zonal band of the SST tendency as wider than 5°S – 5°N , the vertical advection may be underestimated, and the unrealistic thermocline depth is expected in the CZ model (Perigaud and Dewitte, 1996). In the present study, the SST budget is averaged over 5°S – 5°N . Note that qualitatively, the results are not sensitive to the meridional extension of the zonal band of the SST tendency.

3. Flux form of the SST budget

In most of the SST budget studies to reveal the ENSO mechanism, the advection form of the SST equation has been used as Eq. (1) (*e.g.*, Battisti, 1988; Perigaud *et al.*, 1997). The SST budget can be most meaningfully analyzed by using the partial flux form of the SST equation of Eq. (2):

$$\begin{aligned} \frac{\partial T'}{\partial t} = & -u_m \frac{\partial T'}{\partial x} - u' \frac{\partial (T_m + T')}{\partial x} - v_m \frac{\partial T'}{\partial y} \\ & - v' \frac{\partial (T_m + T')}{\partial y} - M(w_m) \frac{\partial T'}{\partial z} \\ & - \{M(w_m + w') - M(w_m)\} \frac{\partial (T_m + T')}{\partial z} \\ & - aT', \end{aligned} \quad (1)$$

$$\frac{\partial T'}{\partial t} = -u' \frac{\partial (T_m + T')}{\partial x} - v' \frac{\partial (T_m + T')}{\partial y}$$

$$\begin{aligned}
& - \{M(w_m + w') - M(w_m)\} \frac{\partial(T_m + T')}{\partial z} \\
& - \frac{\partial(u_m T')}{\partial x} - \frac{\partial(v_m T')}{\partial y} - \frac{\partial(M(w_m) T')}{\partial z} \\
& - aT'.
\end{aligned} \tag{2}$$

Here, T' is the SST anomaly, u' and v' are the anomalous zonal and meridional mixed layer currents, and w' is the anomalous upwelling velocity. It is obtained from the divergence of the horizontal mixed layer currents. The subscript m indicates the prescribed climatological mean quantities. $M(w)$ is w when w is positive, otherwise, $M(w)$ is zero.

Although the net SST tendencies calculated from Eq. (1) and Eq. (2) are identical, the two SST equations bring a different physical interpretation on SST change. For example, the meridional advection of the anomalous SST gradient by the mean current ($-v_m \partial T' / \partial y$) seemingly acts as the positive feedback (Battisti, 1988). But it actually reduces the amplitude of the equatorial SST anomaly by advecting the equatorial heat off the equator (Fig. 1e). This apparent contradiction can be removed if one considers the partial flux form of the SST budget. Because the advection terms by the mean currents and upwelling, including $-u_m \partial T' / \partial x$, $-v_m \partial T' / \partial y$ and $-M(w_m) \partial T' / \partial z$, are separated into a combination of the flux term and the continuity term, for example, $-v_m \partial T' / \partial y = -\partial(v_m T') / \partial y + T' \partial v_m / \partial y$. Then the continuity terms cancel each other by $T' \partial u_m / \partial x + T' \partial v_m / \partial y + T' \partial w_m / \partial z = 0$. Ultimately the net effect of the $-v_m \partial T' / \partial y$ is the divergence of the meridional heat flux $-\partial(v_m T') / \partial y$. During the El Niño, this divergence of the meridional heat flux, in the equatorial region, has a negative value (see Fig. 1e). Therefore, it acts as a damping mechanism. Subsequently the meridional heat flux acts as a redistribution of the equatorial heating to poleward, and drives the meridional scale of the SST to be broadened. It is noteworthy that, as considered in Battisti (1988), if the coupled model does not include the mean meridional current (*i.e.*, no anomalous meridional SST advection by the mean current), then the resultant variation is damped and does not oscillate. Because the large compensating term to the steady damping term $T' \partial M(w_m) / \partial z$, is artificially eliminated.

Figure 1 shows the lag covariance between the local SST tendency, and the normalized NINO3 SST anomaly, as a function of longitude and time lag. A positive lag means that the local SST tendency lags the NINO3 SST anomalies. The SST tendency was averaged over 5°S–5°N, and the contributions from each advection terms appearing in Eq. (2) are separated in the panels. The SST tendency being in-phase with the NINO3 SST anomaly, indicates an amplification of the ENSO anomalies. That being in a quadrature leading the NINO3 SST anomaly,

indicates the transition of the ENSO.

The positive SST tendencies due to the zonal SST advection by anomalous zonal current in the central and eastern Pacific (Fig. 1a), and those due to the vertical thermal flux divergence by the mean upwelling in the eastern Pacific (Fig. 1f), slightly lead the NINO3 SST anomaly. It implies that the two advective thermal effects act to favor the transition and growth of ENSO. They have been considered as the important terms in the ENSO phase transition and growth in the theoretical studies (*e.g.*, Hirst, 1986, 1988; Wakata and Sarachik, 1991; Kang and An, 1998). The SST tendencies due to the vertical thermal advection by anomalous upwelling (Fig. 1c), the divergence of the zonal SST anomaly flux (Fig. 1d), and the meridional SST anomaly flux (Fig. 1e), are nearly in phase with the NINO3 SST anomalies. The positive SST tendency due to the vertical thermal advection by anomalous upwelling, and the negative SST tendency due to both divergences of zonal and meridional thermal flux, act as the growth and damping mechanisms. Eventually those mostly cancel each other. The relatively strong SST tendency due to the vertical thermal advection by anomalous upwelling (Fig. 1c), is attributed to the strong Ekman current in the CZ model. But in reality, this effect is weak. Note that the meridional advection of climatological mean SST gradient by the anomalous meridional current, (Fig. 1b) is relatively weak. In the next section, we will address the roles of the advection of mean SST by anomalous zonal current (zonal advection feedback), and the divergence of the vertical thermal flux by the mean upwelling (thermocline feedback) in detail.

4. ENSO transition and instability mechanisms in the CZ model

On the ENSO time scale, the zonal pressure gradient force accompanying the thermocline depth tilt along the equator is largely in a Sverdrup balance with the equatorial wind stress forcing (*e.g.*, Cane and Sarachik 1981; Philander 1990). This leading balance only constrains the east-west contrast of the thermocline depth. The zonal mean thermocline depth over the equatorial band is not constrained by this balance. The total thermocline depth in the western Pacific, which is determined by adding the zonal contrast and zonal mean thermocline depth anomalies, is also not constrained by this balance. The zonal mean thermocline depth depends on the mass adjustment of the entire tropical Pacific ocean. It may not be in equilibrium with the slowly varying wind forcing, as shown in the ocean GCM experiment (Schneider *et al.*, 1995). This nonequilibrium adjustment between the zonal mean thermocline depth and the wind stress forcing provides the ocean memory that causes the oscillation of the ENSO. It is meaningful and convenient to separate

Fig. 1. Time-longitude section of lag covariance between the normalized NINO3 SST anomaly, and the local SST tendencies due to (a) $-u'\partial(T_m + T')/\partial x$, (b) $-v'\partial(T_m + T')/\partial y$, (c) $-\{M(w_m + w') - M(w_m)\}\partial(T_m + T')/\partial z$, (d) $-\partial(u_m T')/\partial x$, (e) $-\partial(v_m T')/\partial y$, and (f) $-\partial(M(w_m)T')/\partial z$. The SST tendencies are averaged over the 5°S – 5°N zone. The negative values are shaded. Units are $0.1^\circ\text{C month}^{-1}$. Positive time lags indicate the SST tendency lagging the NINO3 SST anomaly.

the thermocline depth into its zonal mean, and zonal contrast. The significant difference is in the time scales of the dynamical adjustment processes for the two fields. In the following section, both zonal mean and zonal contrast of the thermocline depth anomalies are separately applied into the calculation of the

SST budget.

In the CZ model, the anomalous vertical temperature gradient $\partial T'/\partial z$ is referred to $\gamma(T' - T'_{sub})/H_1$, where γ indicates the effective entrainment rate, H_1 is a fixed mixed layer depth of 50 m, and T'_{sub} is the subsurface temperature anomaly just below the

Fig. 2. As in Fig. 1., but for $-\partial(M(w_m)T')/\partial z$, which is the same as $\gamma M(w_m)T'_{sub}/H_1$, where T'_{sub} is calculated by using (a) zonal mean thermocline depth anomaly $[h']$, and (b) zonal contrast of the thermocline depth anomaly h^* .

mixed layer. Using this equation, we can represent the anomalous vertical thermal advection by the mean upwelling as

$$\begin{aligned} -M(w_m)\frac{\partial T'}{\partial z} &= -\gamma M(w_m)\frac{T' - T'_{sub}}{H_1} \\ &= \gamma M(w_m)\frac{T'_{sub}}{H_1} - \gamma M(w_m)\frac{T'}{H_1} \end{aligned} \quad (3)$$

The first and second terms of the *right-hand-side* of Eq. (3) are identical to the vertically integrated vertical thermal flux term $(-\partial(M(w_m)T')/\partial z)$ so-called 'thermocline feedback' and continuity term $(T'\partial M(w_m)/\partial z)$ from H_1 to surface, respectively. It implies thus that the vertical thermal flux at the mixed layer depth is proportional to the subsurface temperature anomaly. Note that the SST tendency due to the continuity term in Eq. (3) is always negatively correlated to SST anomaly because $M(w_m)$ is always positive. The subsurface temperature anomalies strongly depend on the thermocline depth anomalies. Moreover, the subsurface temperature anomaly in the intermediate coupled models, including the CZ model, is parameterized as the function of the thermocline depth anomaly. Thus, we can separate the vertical thermal flux, in other words, the thermocline feedback effect into two parts: one is due to the zonal mean thermocline depth anomaly $[h']$ and the other is due to the zonal contrast of the thermocline depth anomaly $h^* = h' - [h']$.

Figure 2a shows the lag covariance between the local SST tendencies due to the vertical thermal flux divergence by mean upwelling associated with the zonal mean thermocline depth anomalies and the normalized NINO3 SST anomaly as a function of longitude and time lag. Figure 2b is the counterpart of Fig. 2a showing the effect of the zonal contrast field of the thermocline depth anomalies. As in Fig. 1, the SST tendency is averaged over 5°S – 5°N . As shown in Fig. 2a, the SST tendency due to a vertical thermal flux divergence associated with $[h']$ leads the NINO3 SST anomaly by about 1 year (a quarter cycle). That associated with h^* is in phase with the NINO3 SST anomaly. It clearly implies that the vertical thermal flux associated with the zonal mean thermocline depth plays a role in the transition of the ENSO. That associated with the zonal contrast thermocline depth plays a role in the growth of the ENSO. By using the diagnostic method, the roles of thermocline feedback in the ENSO phase transition and growth can be rather clearly demonstrated. Note that the relatively strong SST tendency in the eastern Pacific in Fig. 2a is due to the strong mean upwelling velocity, and the strong sensitivity of T'_{sub} to thermocline depth anomaly in the shallow mean thermocline depth area.

The anomalous vertical-mean zonal current (u'_o) is directly linked to the meridional gradient of

Fig. 3. As in Fig. 1., but for (a) $-[u'_o]_e \partial(T_m + T')/\partial x$, where u'_o is the equatorial zonal mean zonal current anomaly. (b) $-u'_o^* \partial(T_m + T')/\partial x$, where u'_o^* is the zonal contrast of the zonal current anomaly.

the thermocline depth anomaly through the semi-geostrophic balance (Jin, 1997b; Jin and An, 1999). We can also divide the zonal current anomaly into two parts: one is the equatorial zonal mean zonal current anomaly $[u'_o]_e$, and the other is the zonal contrast field. The counterpart of the equatorial zonal mean zonal current anomaly is $u'_o - [u'_o]_e = u'_o^*$. The equatorial zonal mean zonal current is a geostrophic current, which must satisfy $\beta y[u] = -g' \partial[h]/\partial y$.

In Fig. 3a, we show the lag covariance between the SST tendency due to the advection of the climatological mean SST by the anomalous equatorial zonal mean zonal current $-[u'_o]_e \partial(T_m + T')/\partial x$ and the NINO3 SST anomalies. In Fig. 3b, we show those due to the zonal contrast field of the zonal current anomaly $-u'_o^* \partial(T_m + T')/\partial x$. Here, the zonal SST advection by the shear current is ignored, because it is smaller than that by the vertical-mean zonal current. In the calculation of the equatorial band average of $[u'_o]_e \partial(T_m + T')/\partial x$, we also assumed a simple meridional structure of $[u'_o]_e$ as $[u'_o]_e = [u'_o]_e e^{-y^2/2}$. Under this assumption, and the geostrophic balance, one further finds that $[u'_o]_e$ is proportional to $[h']$. Thus, it is not surprising that, as shown in Fig. 3a, $-[u'_o]_e \partial(T_m + T')/\partial x$ always leads the NINO3 SST anomaly by about 1 year as the vertical thermal flux does. It mostly appears in the central/eastern Pacific where the large zonal gradient of mean SST occurs. $-u'_o^* \partial(T_m + T')/\partial x$ is almost in phase with

the NINO3 SST anomalies (Fig. 3b), and it is relatively weak. Hence the advection of the mean SST by the equatorial zonal mean zonal current anomaly affects the transition of the ENSO, and that by the zonal contrast field affects the growth of the ENSO.

As shown in Figs. 2 and 3, the SST tendencies induced by the vertical thermal flux associated with the zonal mean thermocline depth anomaly, and the zonal SST advection by the equatorial zonal mean zonal current anomaly, act as the major contributors for the ENSO transition. In order to investigate the importance of zonal advection feedback in the ENSO further, we carry out a similar approach utilized in Zebiak and Cane (1987). Zebiak and Cane had demonstrated the dependence of the oscillatory character on the zonal mean thermocline depth anomaly, by artificially disturbing the effect of the zonal mean thermocline depth anomaly. According to Zebiak and Cane (1987), when the zonal mean thermocline depth in their coupled simulation is artificially removed from the calculation of SST change, the interannual variability in the model completely disappears. Reducing it by half, or doubling results in significant changes in the characteristic of the interannual oscillation of the model. The period changes from about 4 years to about 5–6 years and about 2 years, respectively, for these two cases.

The time series of the NINO3 SST anomaly calculated from the CZ model, in which the advection of

Fig. 4. Time series of the NINO3 SST anomaly of standard run (heavy line) and test run (thin line) with (a) effects of variations in the zonal SST advection by the equatorial zonal mean zonal current suppressed, (b) reduced by 50 %, and (c) increased by 200 %. The first year in this figure corresponds to the twenty-first year from the initial condition.

mean SST by the equatorial zonal mean zonal current anomaly is disturbed, is shown in Fig. 4. The same index calculated from the CZ model without disturbance is also shown. Without the advection of mean SST by the equatorial zonal mean zonal current anomaly (Fig. 4a), the oscillation period becomes much longer. If this SST advection is partially suppressed (Fig. 4b), the transitions between the cold and warm states are slightly retarded. If this effect is artificially increased (Fig. 4c), the oscillation period is shortened. When we apply the same experiment to the conceptual model of Eq. (6) in Jin and An (1999), we have a similar result as in the CZ model. For instance, if we remove the contribution of the zonal advection feedback to the transition of ENSO in the conceptual model, the oscillation period increases from 3.2 years to 4.7 years. If we increase it by doubling the value, the resulting period reduces to 2.5 years. Those results consistently illustrate that the oscillatory character depends on the advection of the mean SST by the equatorial zonal mean zonal current anomalies, in a similar way as does the thermocline feedback involved in the zonal mean thermocline depth anomalies. However, the sensitivity of the oscillatory character to changes in the equatorial zonal mean zonal current anomalies, is less dramatic than that in the zonal mean ther-

mocline depth anomalies in the CZ model. Thus, it seems that the vertical thermal flux associated with the zonal mean thermocline depth anomaly plays a somewhat more dominant role in the phase transition of the ENSO.

5. Summary and concluding remarks

A diagnostic study of the SST budget in the CZ model is carried out to understand the transition and instability mechanisms of the ENSO. By adopting the partial flux form of the SST equation, two processes responsible for the ENSO phase-transition and growth are clearly identified. In the partial flux form of the SST budget, it is verified that the SST change is mostly accomplished by the vertical thermal flux by the mean upwelling $\partial(M(w_m)T')/\partial z$ (thermocline feedback), and the advection of the climatological mean SST by the anomalous zonal current $u'_o \partial(T_m + T')/\partial x$ (zonal advection feedback). The thermocline feedback associated with the zonal mean thermocline depth anomaly, and the zonal advection feedback by the equatorial zonal mean zonal current anomaly are responsible for the phase transition of the ENSO. Those associated with zonal contrast fields are responsible for the growth of the ENSO. Although the thermocline feedback, as well as the zonal advection feedback in the SST change

significantly contributes to the phase transition and growth of the ENSO, in case of the transition, the zonal advection feedback seems to play a secondary role. Note that the two processes can be closely linked, because of the geostrophic balance between the meridional gradient of the thermocline depth, and the zonal current.

The delayed oscillator theory (Battisti and Hirst, 1989), and the recharge oscillator theory (Jin, 1996, 1997a, b), had mentioned that the vertical thermal flux by mean upwelling associated with the thermocline depth, is a major contributor to the phase transition of the ENSO. On the other hand, the role of the advection of the mean SST by the anomalous zonal current has been stressed by Picaut *et al.* (1996, 1997). In the study of Jin and An (1999) and this study, it is clearly demonstrated that the non-equilibrium adjustment of the zonal mean thermocline depth anomaly to the wind stress anomalies, acts to favor the transition of the ENSO through the two advective thermal processes, including the thermocline and zonal advection feedbacks.

As found in Jin and An (1999) and this study, the transition mechanism from warm to cold is accomplished as follows: during the warm event, both the anomalous wind in the central Pacific and the SST anomalies in the eastern Pacific, increase by the so-called Bjerknes positive feedback mechanism. At the same time, the westerly wind anomaly induces the Ekman flow meridional mass flux convergence near the surface, whereas the meridional mass flux in the entire upper layer is diverged from the equator due to the Sverdrup transport, which is dominant. The meridional mass flux, and the mass fluxes at the eastern and western boundaries due to the equatorial wave reflection, drive the negative tendency in zonal mean thermocline depth anomaly in the equatorial region. The positive tendency is induced off the equator, as mentioned in Wyrski (1986) and Jin (1997b). The westerly wind anomaly leads to the decrease of equatorial zonal mean thermocline depth, and the increase of the off-equatorial zonal mean thermocline depth. The shoaling in the entire equatorial band, and deepening of the off-equatorial band, generates the north-south pressure gradient and results in the westward geostrophic zonal mean current. In the result, the negative SST tendency in the equatorial central/eastern Pacific is gradually generated by the vertical thermal flux due to the shoaling of the zonal mean thermocline in the eastern Pacific, and the zonal SST advection by the anomalous equatorial zonal mean westward current in the central/eastern Pacific (Figs. 2a and 3a). Both thermal processes slowly erode the warming tendency due to the positive feedback, and eventually turn the warm phase into the cold phase. After the cooling is started, it is amplified by positive feedback. The transition from cold to warm can be

addressed as the reversed case of the transition from warm to cold. These findings support the new conceptual model proposed for the ENSO by Jin and An (1999).

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Cane-Zebiak モデルにおける ENSO の位相遷移と成長に果たす 東西移流フィードバックの役割

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Cane-Zebiak モデルの SST 収支を解析することによって ENSO の反転と成長のメカニズムを診断的に調べた。ENSO の位相遷移と成長に直接関係した SST 変化率は二つのプロセスに帰する。すなわち、平均湧昇流による亜表層水温の鉛直移流 (温度躍層フィードバック) と東西流アノマリによる気候平均 SST の東西移流 (東西移流フィードバック) である。ENSO の位相遷移と成長に対する寄与は赤道温度躍層深度アノマリと東西流アノマリを東西平均場と東西偏差場に分解することによって系統的に分離することができる。東西平均温度躍層深度アノマリと関連した温度躍層フィードバックと赤道東西平均東西流アノマリによる東西移流フィードバックが ENSO の位相遷移をもたらしていることがわかった。また、東西偏差場と関連したこれらのプロセスは ENSO の成長に寄与している。SST 変化における二つのプロセスはほとんど等しい重要度で ENSO の位相伝播と成長に寄与している。さらに、温度躍層の南北傾度と東西流との間の地衡流平衡の結果として両プロセスは密接に関連している。これらの知見は Cane-Zebiak モデルにおける ENSO の概念的理解には両プロセスが含まれるべきであることを示唆している。