NUMERICAL STUDY ON THE ROLE OF VORTICAL AND DIVERGENT COMPONENTS OF WIND STRESS IN ENSO CYCLE

GUAN Zhaoyong (管兆勇) and LIU Xuanfei (刘宣飞)

Department of Atmospheric Sciences, Nanjing Institute of Meteorology, Nanjing 210044

Received July 9, 1999; revised May 10, 2000

ABSTRACT

The 1980—1991 monthly mean FSU (Florida State University) wind stress data are decomposed into a vortical and a divergent component with each of which to force the model ocean in the context of a two-layer tropical Pacific model. Evidence suggests that for the seasonal variation the ocean forcing does not produce a realistic cold tongue using either of the components and the tongue will act be effectively improved in its intensity and pattern even if the components are doubled or halved: the utilization of climatic mean wind stress (no decomposition is done of the wind stress) that contains its seasonal variation will lead to a realistic SST distribution on which is imposed, separately, the interannual anomalies of each of the components so as to get the SSTA pattern: under the action of the interannual anomaly of the vortical (divergent) component there arises quite intense SSTA oscillation marked by noticeable ENSO periods (feeble SSTA with higher oscillation frequency for obscure ENSO periods). thereby illustrating that the roles of the two components differ from each other in the genesis of SST variation on a seasonal and an interannual basis such that a realistic cold tongue pattern follows under the joint effects on the model ocean of the two components of wind stress while rational El Nino/La Nina phenomena result under the forcing of an anomalous wind stress vortical component. Moreover, the divergent component is inattenuable in generating a mean climatic condition of the ocean sector but of less importance compared to the vortical component in ENSO development.

Key words: ENSO, cold tongue, vortical component of wind stress, numerical experiment

1. INTRODUCTION

El Nino/La Nina events in the equatorial eastern Pacific have received much attention from meteorologists and oceanographers of the world because of their great impacts on global climate. Over past decades the genesis, development and prediction of ENSO have been explored extensively from a range of perspectives in different aspects and the problem has been and is being dealt with by many international projects like WCRP and CLIVAR. which contribute to the advances in its study. Scientists have revealed that the formation, development, maintenance and decay of El Nino/La Nina episodes are the result of atmosphere-ocean interactions. in which the dynamic forcing of wind stress (WS) on the

The work is supported jointly by the National Natural Science Foundation of China (Grant 19775265) and Research Starting Funds for Returned Scientific Personnel under the PRC Education Commission.
sea and the thermal forcing of SSTA on the atmosphere are thought to be the important
dactors. Accordingly, air and sea can be coupled, leading to theories for interpreting
ENSO, such as the positive feedback relation between trade wind intensity and equatorial
eastern Pacific SSTA (Bjerknes 1966), and the propagation, reflection and instability of
air-sea coupling wave (Philander et al. 1984; Schopf and Suarez 1988). Nevertheless, the
mechanism of ENSO cycle and its prediction remain unsolved entirely. As a consequence,
the ENSO study is still of interest today.

As we see, the WS is crucial to ENSO cycle. But what kind of information, which is
important to SST variation. does the WS contain? They can be grouped as follows: 1) 
information of the WS climatology that has considerable effect on SSTA amplitude (Guan
et al. 2000a). And the interactions between seasonal variation and interannual anomaly of
SST (e.g., phase-lock) have been reported by more than one writer (Xie 1995; 
Tziperman et al. 1997): 2) information on WS period, which results from air-sea
interactions, but the WS effect on SST variation differs at different time scales
(Rasmusson and Carpenter 1982; Miller 1984; Yue et al. 1997). Studies show that an
anomalous WS at ENSO time scale constituting 30% of the total variance can produce a
period of variation of SSTA comparable in size to that which would be generated by the
primitive WS field (Guan et al. 2000b): 3) information on the horizontal structures,
e.g., those of equatorial atmospheric waves, consisting of travelling and standing types; and
4) information on WS components, referring to the vortical and the divergent
components. As we know, under the action of Ekman pumping, the vortical part gives
rise to the upwelling and subsidence of the sea water. The present study concerns the role
of the WS vortical and divergent components on ENSO cycle by means of numerical
experiments.

II. MODEL AND SCHEME

1. Model

1991), Balmaseda et al. (1994) and Haines et al. (1996) made approach to the ENSO
cycle mechanism and its prediction mostly in terms of an atmosphere-ocean coupling model
of moderate complication, which consists of a two-layer dynamic-oceanic model coupled to
a statistical-atmospheric model. Here we employ only the sea model that is composed of $N$
$(=2)$ active levels from top to bottom below which the sea water is still. The model we
use has the expressions as

$$
\frac{\partial}{\partial t} + \frac{\partial}{\partial x} \mathbf{u} + \frac{\partial}{\partial y} \mathbf{v} = f \times \mathbf{h} + \mathbf{v} \cdot \nabla \mathbf{h}, \quad \frac{\partial}{\partial t} \rho \mathbf{h} + \frac{\partial}{\partial x} \rho \mathbf{u} = \mathbf{M}_i (\varepsilon_{i, i-1}) + \mu_i \nabla \cdot \mathbf{h}, \quad (1)
$$

$$
\frac{\partial}{\partial t} + \frac{\partial}{\partial x} \mathbf{u} + \frac{\partial}{\partial y} \mathbf{v} = \mathbf{D}_i + \xi \nabla^2 \mathbf{h}, \quad (2)
$$

$$
\frac{\partial}{\partial t} + \frac{\partial}{\partial x} \mathbf{u} + \frac{\partial}{\partial y} \mathbf{v} = \mu_i \mathbf{Q}_i + \mathbf{B}_i (\varepsilon_i, \varepsilon_{i-1}) + \kappa \nabla^2 \mathbf{T}_i, \quad (3)
$$

where $i = 1, 2, \cdots, N$. $\mathbf{v} (\mathbf{u}_i, \mathbf{v}_i)$ denotes the horizontal velocity in the $i$th layer; $\mathbf{h}$, $\mathbf{D}_i$, and $\mathbf{T}_i$ the depth, pressure and temperature, respectively, in the $i$th layer; $\mu$ is evaluated
in such a way that $\mu = 1$ for $i = 1$ and $\mu = 0$ for $i \neq 1$: the water at $(N+1)$ layer is stagnant with temperature $= 5^\circ C$. $-\nabla p / \mu$ stands for the pressure gradient force. $Q$ and $\tau$ the heat flux and WS vector acting on sea level (the first model layer), respectively. $\epsilon_i$ is the entrainment or extratrainment at the interface between the $i$th and $(i+1)$th layers, thereby causing the exchange of mass, momentum and heat between the layers (the salinity change is not considered for the study Pacific region). $\epsilon_i$ and its related variables in Eqs. (1) to (3) are given in Eqs. (4) to (7).

$$\epsilon_i = \frac{\eta}{2} \left[ \frac{(H_{i+1} - h_i + |H_{i+1} - h_i|) |H_{i+1} - h_i|}{H_i} \right] + \frac{(H_{i+1} - h_i + |H_{i+1} - h_i|) |H_{i+1} - h_i|}{H_i} \left[ \frac{(H_{i+1} - h_i + |H_{i+1} - h_i|) |H_{i+1} - h_i|}{H_i} \right] .$$

(4)

with $\eta = 0$ at $i = 0$ or $i > N - 1$, and $\eta = 1'$ at $1 \leq i \leq N - 1$. suggesting that for the $i$th layer depth $< H_i$, mass adjustment will make the depth increased and for the $i$th layer depth $> H_i$, the depth decreased. In fact, for the 2-layer model, only $\epsilon_i$ is meaningful.

For mass conservation in an equation of continuity, $D_i$ is given as:

$$D_i = \epsilon_i - \epsilon_{i-1},$$

(5)

and for the entrainment and extratrainment, the exchange of momentum is denoted by

$$M_i = \frac{1}{2} \left[ (\epsilon_i + |\epsilon_i|) (T_i - T_{i-1}) \right]/\rho_i - \frac{1}{2} \left[ (\epsilon_{i-1} - |\epsilon_{i-1}|) (T_i - T_{i-1}) \right]/\rho_{i-1}.$$

(6)

and the exchange of heat by

$$B_i = -\frac{1}{2} \left[ (\epsilon_i + |\epsilon_i|) (T_i - T_{i-1}) \right]/\rho_i.$$

(7)

Equation (7) signifies that the entrainment of water with different temperatures into a given layer will give rise to temperature change there.

In Eq. (3) the acting-on-sea-surface thermal flux $Q$, has the same form as in Balmaseda et al. (1994), viz.,

$$Q_i = Q_0 - (dQ/dT)_0 (T_i - T_0).$$

(8)

where $Q_0$, $T_0$, $(dQ/dT)_0$ and $T_1$ are the month-dependent climatic mean heat flux, SST, relaxing factor (always negative) and the first model layer temperature, respectively, based on the calculation of observations. The sea-level thermal flux $Q$, of Eq. (8) is employed to obtain stable climatic state by means of the climatic experiment and if forcing experiment is conducted with the aid of sea forcing of the WS containing interannual oscillation or if air-sea coupling simulation is undertaken the sea-level thermal flux is given by

$$Q_i = Q_0 - (dQ/dT)_0 (T_i - T_0) - 0.2 (dQ/dT)_0 (T_i - T_1) -$$

(9)

where $T_m$ stands for the stable SST from the climatic run and introduction of the factor 0.2 makes $T_1$ approximate to $T_m$.

The model domain covers 30.75° N - 30.75° S and 122.25° E - 68.25° W with horizontal resolution of 1.5° x 1.5°. For $N = 2$, the model parameters are shown in Tables 1 and 2 (from Balmaseda et al. 1994).

2. Design of the Experimental Scheme

The experiment is threefold: 1) a control run is done to examine the model ability to
simulate SST climatic mean state and El Nino/La Nina events in comparison to the outcome from the other runs: 2) we will see whether a reliable SST mean regime is generated by the forcing of either of the WS climatic mean vortical and divergent components. If not, we proceed to the next: 3) based on the climatic mean state from the control run, can a rational El Nino or La Nina phenomenon be generated with each of the two interannual anomalous WS components imposed separately upon the climatic mean WS field (undecomposed)?

**Table 1. Parameters and Their Values for the 2-Layer Oceanic Model**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H_s )</td>
<td>100 m</td>
<td>entrainment depth</td>
</tr>
<tr>
<td>( H_o )</td>
<td>100 m</td>
<td>entrainment depth</td>
</tr>
<tr>
<td>( t_e )</td>
<td>1 d</td>
<td>entrainment time scale</td>
</tr>
<tr>
<td>( t_r )</td>
<td>500 d</td>
<td>entrainment time scale</td>
</tr>
<tr>
<td>( \phi )</td>
<td>500 m(^2) s(^{-1})</td>
<td>horizontal viscosity coefficient</td>
</tr>
<tr>
<td>( \zeta )</td>
<td>500 m(^2) s(^{-1})</td>
<td>horizontal mixing coefficient</td>
</tr>
<tr>
<td>( \kappa )</td>
<td>500 m(^2) s(^{-1})</td>
<td>thermal diffusion coefficient</td>
</tr>
</tbody>
</table>

**Table 2. Demarcated Regions of the Pacific under Research**

<table>
<thead>
<tr>
<th>Region</th>
<th>Longitude</th>
<th>Latitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nino 1</td>
<td>90—80°W</td>
<td>10—5°S</td>
</tr>
<tr>
<td>Nino 2</td>
<td>90—80°W</td>
<td>5°S—EQ</td>
</tr>
<tr>
<td>Nino 3</td>
<td>150—90°W</td>
<td>5°S—5°N</td>
</tr>
<tr>
<td>Nino 4</td>
<td>150°E—150°W</td>
<td>5°S—5°N</td>
</tr>
<tr>
<td>EQ3</td>
<td>150°E—170°W</td>
<td>5°S—5°N</td>
</tr>
<tr>
<td>EQ2</td>
<td>170—130°W</td>
<td>5°S—5°N</td>
</tr>
<tr>
<td>EQ1</td>
<td>130—90°W</td>
<td>5°S—5°N</td>
</tr>
</tbody>
</table>

Note: the two tables come from Balmaseda et al. (1994).

(1) *Mean climatic regime experiments*

By climatic experiments we mean that under the effect of monthly WS and heat flux fields without interannual variation, the model ocean experiences adjustment in a number of model years to reach a stable state, that is, the ocean variable is very little different in value from the previous and subsequent model year on a monthly basis. For the present
model it needs about 4 years to complete the adjustment from a horizontally homogeneous initial field \((u, v, h, T)_{t=0} = (0, 0, h_0, T_0)\). but this paper presents a 10-year integration to allow the ocean to be fully adjusted. The wind stress \(\tau = \tau_s + \tau_a\) is dissolved into

\[\tau = \tau_{s} + \tau_{a} + \tau_{o}\]  

where \(\tau_s\), is regarded as containing seasonal variation only as in the case of \(T_s, Q_s\) and \(T_o\), and \(\tau_a\) is the interannual anomaly with respect to \(\tau\), and set to be zero in the climatic experiments. \(\tau\) is resolved into

\[\tau = \tau_{s} + \tau_{a}\]

where \(\tau_{s}\) and \(\tau_{a}\) represent the vortical and divergent components of \(\tau_s\), respectively. We impose the effect of \(\tau_s\), \(\tau_{s}\) and \(\tau_{a}\) upon the model ocean to formulate three climatic experiments. denoted as CCC0. CSC1 and CSC2. in order.

(2) **Anomalous forcing experiment**

The monthly mean variables (such as SST or \(T_s\)) of the last model year and the oceanic conditions at the last model hour from the climatic experiment are employed as the reference factors and initial field, respectively. after which a forcing run is conducted. And in the forcing experiment the WS field experiences interannual anomaly. under whose forcing an El Nino event should be reproduced by the oceanic model.

No doubt. \(\tau_s\) can be decomposed into a vortical and a divergent component. viz.

\[\tau = \tau_{s} + \tau_{a}\]

with ocean forcing \(WS\) \(\tau = \tau_{s} + \tau_{a}\) taken. we have the control experiment on anomalous climate variation. denoted as CCC1. with \(\tau = \tau_{s} + \tau_{a}\) used as the forcing on sea-level \(WS\). we have the sensitivity experiment. denoted by FSC1. and with \(\tau = \tau_{s} + \tau_{a}\) used. we get another sensitivity experiment (FSC2).

The 1961 - 1991 FSU (Florida State University) wind stress \(\tau = (\tau_s, \tau_a)\) data (Balmaseda et al. 1994) are utilized as the forcing on the model ocean in our study with the SST from GISST dataset (Parker et al. 1995).

III. **WIND STRESS VORTICAL AND DIVERGENT PROPERTIES AND EQUATORIAL PACIFIC COLD TONGUE**

The existence of a cold tongue in the equatorial Pacific is an important feature in the SST distribution. An oceanic model should be able to imitate a realistic cold tongue pattern and the model we use here serves the purpose. Figure 1 portrays the SST patterns for January. April. July and October of model year 10 from CCC0 (right-hand panels) and the fields for the same months averaged over 45 years from the GISST dataset (left-hand panels).

We notice therefrom that the simulated patterns are very similar to the observed ones and the seasonal variations of the cold tongue and 'warm pool' are rational. Furthermore, simulation shows the oceanic currents and equatorial counter-flow to be analogous to the climatic mean (figure not shown), indicating that the model is efficient in imitating the sea climatic mean regime. Then. what will the climatic mean SST patterns be if the schemes CSC1 and CSC2 are used?

Figure 2 depicts the SST patterns for January. April. July and October of model year
10 from CSC1 (left panels) and CSC2 (right panels). One can notice therefrom that no such cold tongue pattern as in Fig. 1 will emerge by imposing either of the WS components on the sea surface instead of the primitive WS. suggesting that the cold tongue simulation is unsuccessful. The vortical and divergent components come from the decomposition of the WS containing seasonal variation so that their values are smaller than the original WS. To examine whether the failure to simulate the cold tongue is ascribed to insufficiently strong components we have performed two additional experiments in such a way that the doubled in value components are put into the run. leading, however, to no noticeable improvement (figure omitted) and that the halved into the experiment does not result in a reliable cold tongue distribution (figure not shown). We did so because the components differ in structure from the original WS.

It follows that in spite of the fact that the vortical component of climatic mean WS is responsible for the Ekman pumping in the ocean and the divergent one for directly driving sea surface water. they are not vigorous enough to generate sufficiently intense horizontal mass divergence in the equatorial eastern Pacific so as to produce and sustain quite strong sea water upwelling there.

As such, the two WS components are crucial to the formation and maintenance of ocean climatic mean condition.
IV. ANOMALOUS WS VORTICAL AND DIVERGENT COMPONENTS IN RELATION TO EL NINO/LA NINA EPISODES

We have just investigated the relation of cold tongue simulation to the components of climatic mean WS. In effect, when the cold tongue imitation is a failure, so is the SST anomaly simulation. On the basis of CSC1 and CSC2, an ensuing anomalous climatic experiment was conducted in such a way as to separately impose the vortical component of WS (consisting of the climatic mean and interannual anomaly) and the divergent component of WS on the sea. showing that in Nino 3, the SST amplitude and period differ greatly from those based on the analysis of actual measurements. In contrast, our model is capable of simulating El Nino/La Nina events, meaning that their occurrence bears a close relation to the existence of a cold tongue.

Then, is it likely to imitate a rational El Nino or La Nina event under the action of the interannually anomalous vortical or divergent component in the presence of a reasonable pattern of a cold tongue in the model oceanic climatic mean condition? To answer the question, we made experiments in virtue of the schemes CCC1, FSC1 and FSC2.

Figure 3 delineates Nino 3 SST anomaly curves from the three schemes where the dotted line reveals each of the events in agreement with observations (see Fig. 3c). This demonstrates the applicability of our model.

Comparison of Figs. 3a and 3b shows that the interannual anomaly of the vortical
component is such as to drive the ocean to generate a rational SSTA variation. The dotted line of Fig. 3a shows the successful imitation of every El Nino episode in the time span. The FSC1-generated information on SSTA amplitude and phase at ENSO time scale is close to that from CCC1 whereas the SSTA amplitude and phase from CSC2 (for divergent forcing) differ vastly from CCC1, thereby illustrating that the anomalous vortical component plays a more important role in the formation and maintenance of El Nino/La Nina events compared to the divergent component. Why does it so? Let us investigate first the oceanic dynamic response to the WS with focus on the depth adjustment of the first model layer under the WS forcing. Figures 4a and 4b delineate the longitude-time sections along the equator for the anomaly of the first model layer depth \( h_1 \) in the 1961—1990 from FSC1 and FSC2, respectively. We see therefrom that the depth anomaly can be excited by either of the anomalous components and it migrates eastward, which is the east-moving Kelvin waves. But comparison of Fig. 4a and Fig. 4b shows two distinct features: 1) the amplitude generated by the anomalous vortical component is considerably bigger and 2) the temporal frequency of the depth anomaly under the divergent forcing is remarkably higher compared to the other. From model equations (3), (4) and (7) we get
\[ T_{\omega} \propto \xi_0 \int h_{1\omega} dt. \] (13)

where \( \xi_0 \) is a factor related to the difference in mean temperature between the first and second model layers. From Exp. (13) we notice that the range of SSTA \( (T_{\omega}) \) variation is associated with the time integration length of the first layer depth anomaly \( h_{1\omega} \). Set \( h_{1\omega} = \alpha \cos \omega t \) and we have

\[ T_{\omega} \propto \frac{\xi_0 \alpha}{\omega} \sin \omega t + C. \] (14)

We see therefrom that the SSTA amplitude depends on the frequency and Kelvin wave amplitude in such a way that the higher the frequency, the smaller the SSTA amplitude; the lower the frequency and hence the longer the period, the larger the amplitude would be; the bigger the Kelvin wave amplitude, the greater the SSTA amplitude.

From the information on amplitude and frequency of the depth anomaly of the first model layer given by FSC1 and FSC2 of Fig. 4, we are permitted to determine through Exp. (14) the basic features of SSTA variation in Figs. 3a and 3b. Besides, we observe from Exp. (14) that the variation of the depth anomaly is by \( \pi/2 \) ahead of the SSTA. Why does \( h_{1\omega} \) show the characteristics of its amplitude and frequency? That is ascribed partially to Ekman pumping. In the equatorial Pacific, particularly in the eastern segment, the

---

Fig. 4. 1961-1990 longitude-time sections along the equator for the depth anomaly of the first model layer \( h_{1} \) from FSC1 (a) and from FSC2 (b). With shaded areas for \( h_{1\omega} < 0 \) and contours spaced at 250 cm.
ratio of variance of the vorticity to that of the divergence in the interannual anomalous WS exceeds 1.0, suggesting that the vorticity is rather big (figure not shown) and under the effect of Ekman pumping strongly anomalous upwelling takes place there while the direct driving sea surface by the divergent component is unimportant in the El Nino/La Nina development. On the other hand, the anomalous vortical component contains remarkable low-frequency part as opposed to the divergent. Figure 5 presents the equatorial longitude-time cross sections of zonally vortical and divergent components, indicating the lower frequency of the vortical zonal component compared to the other, and east-travelling WS disturbances. Since the zonal wind disturbance relative to the atmospheric Kelvin wave is vortical, the anomalous WS vortical component has the east-migrating ingredient.

V. CONCLUSIONS

From the foregoing analysis we come to the following:

(1) As far as seasonal variation is concerned, a rational cold tongue cannot be produced in the model ocean under the forcing of either of the WS components and the tongue remains unreasonable in intensity and distribution even if each of the components is doubled or halved in magnitude. The adoption of climatic mean WS containing seasonal variation (no separation done) leads to a realistic SST pattern, or which is imposed separately the interannual anomaly of each of the vortical and the divergent components to force the model ocean for an SSTa pattern.

(2) Under the influence of interannually anomalous vortical (divergent) component, quite intense (feeble) SSTa oscillations will follow, exhibiting noticeable (unmarked) ENSO periods.

The above results show that the WS vortical and divergent components play a distinct role in generating SST seasonal and interannual variation, implying that a reasonable cold tongue pattern emerges only under the joint action of the two components on the model ocean. However, it is the forcing of the anomalous vortical component that causes rational El Nino/La Nina phenomena. In addition, the WS divergent component is in negligible in the genesis of oceanic climatic mean condition but less important than the vortical
component to the sea for ENSO development.

It should be noted that ENSO cycle is associated with multiple factors (see Wallace et al. 1998; Neelin et al. 1998; Latif et al. 1998) and here we present only the influence of the WS structure on SST variation. Our model needs to be improved when used in some regions and cases for El Nino/La Nina simulations (e.g., the simulated 1982/1983 SSTA is weaker than the observed. see Balmaseda et al. 1994). The introduction of interannually anomalous heat flux into the model can give rise to conspicuous variation of SSTA amplitude and the incorporation of the time series field consisting of thermal flux with standard deviation of 20 W m$^{-2}$ derived from NCEP/NCAR reanalysis (Kalnay et al. 1996) will lead to the interannual variation of 0.5°C SSTA amplitude at ENSO time scale regardless of the existence of the WS interannual anomaly. This demonstrates that heat flux is an important factor in atmosphere-ocean interaction as well (see Wallace et al. 1998; Neelin et al. 1998; Latif et al. 1998).

The authors are grateful to the Nanjing Atmospheric Data Center under the Department of Geoscience, the National Natural Science Foundation of China for its provision of datasets and to the NCEP/NCAR for its reanalysis unloaded from http://www.edc.noaa.gov.

REFERENCES


