A Comparison of the Transition of Equatorial Waves between Two Types of ENSO Events in a Multilevel Model

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ABSTRACT

The differences in the transitions of equatorial mixed Rossby–gravity (MRG) waves to off-equatorial tropical depression (TD)-type disturbances during ENSO events are investigated with a global baroclinic anomaly model. The model reproduces reasonably the perturbation evolution within realistic three-dimensional summer mean states corresponding to El Niño (EN) and La Niña (LN) years. Based on wave structure and energetics diagnosis, the results indicate that, following the longitudinal shift of the favorable environmental fields, the wave characteristics are altered accordingly. In the presence of a circulation–convection feedback, the wave train exhibits more rapid growth, a more eastern location of transition, and a more northward-shifting component during EN years than during LN years. The convective heating acts as a leading energy source to supply the wave growth and the increase in eddy kinetic energy is directly attributed to barotropic conversion in the monsoon region.

Sensitivity experiments show that the dynamic effect alone fails to capture the observed wave behaviors although the damped modes also experience a scale contraction and a slight northward migration. The near-surface thermodynamic fields related to sea surface temperature (SST) and low-level specific humidity can play a crucial role in the scale contraction and the propagation characteristics for tropical synoptic waves. The heating feedback scheme combining the actions of SST and low-level moisture can amplify and accelerate the modification of wave characteristics initiated by the dynamic effect, producing a tighter wave structure and steering the wave train toward the warmer and moister ocean.

1. Introduction

Synoptic waves are salient over the tropical western North Pacific (WNP) during boreal summer. In general, these off-equatorial waves are referred to as tropical depression (TD)-type disturbances (Takayabu and Nitta 1993) because they are wavelike systems consisting of alternating cyclonic and anticyclonic circulations that extend north-westward from the equatorial region. A number of observational studies have revealed that TD-type disturbances propagate north-westward over the WNP, featuring a wavelength of about 3000 km and a period of 4–8 days (e.g., Lau and Lau 1990; Chang et al. 1996; Sobel and Bretherton 1999). Furthermore, the TD-type disturbances are closely associated with equatorially trapped mixed Rossby–gravity (MRG) waves because of the proximity and even overlapping of their wavenumber–frequency ranges (Wheeler and Kiladis 1999). During boreal summertime, westward-propagating MRG waves along the equator can transit to TD-type disturbances while penetrating into the monsoon region over the WNP. This transition is accompanied by a gradual change in the wavenumber, the phase speed, and the propagation direction (e.g., Liebmann and Hendon 1990; Takayabu and Nitta 1993).

TD-type disturbances are believed to favor the formation of tropical cyclones (TCs) over various ocean basins in the boreal summertime (Frank and Roundy 2006). After the removal of TC-related contamination in equatorial waves, Schreck et al. (2011) also found that roughly twice as many TCs are attributed to TD-type disturbances as to equatorial Rossby (ER) waves, MRG waves, Kelvin waves, and the Madden–Julian oscillation (MJO). Dickinson and Molinari (2002) investigated a typical case in 1987, in which TCs formed repeatedly during the transition of MRG waves to off-equatorial TD-type
distrurbances. Insight into the variation of TD-type disturbances can help advance the understanding of the diversity of TC activity and improve TC prediction on a variety of time scales.

From the climatological viewpoint, the summer monsoon system plays a crucial role in the characteristics and evolution of tropical synoptic waves over the WNP. In terms of dynamic effect, the summer monsoon circulation is characterized by a strong cyclonic shear and convergence of zonal winds, which is favorable for the barotropic conversion of mean-flow kinetic energy to eddy kinetic energy (Maloney and Hartmann 2001). The convergence of trade southwesterly and easterly winds over the tropical WNP can produce a preferred region in which a wave accumulation process occurs, leading to an increase in the wave amplitude and a decrease in the wave scale (Webster and Chang 1988; Liebmann and Hendon 1990). These mechanisms were represented in a linearized vorticity equation in Aiyyer and Molinari (2003), who utilized a linear shallow-water model to simulate the evolution of equatorial MRG waves in an idealized background state similar to the active phase of the MJO. In addition, the easterly vertical shear in the tropical monsoon region can favor trapping wave energy in the lower troposphere. Using a two-layer theoretical model, Wang and Xie (1996) simulated the growth of ER waves in the presence of spatially uniform easterly vertical shear. They found that when asymmetric vertical shear was imposed with easterly shear extending well north of the equator, the ER wave growth occurred only in the Northern Hemisphere. With a nonlinear barotropic model, Kuo et al. (2001) confirmed that variations in mean flow contribute to the transition and growth of tropical waves. On the other hand, the wave-train growth is also closely related to condensation heating in the middle troposphere. Previous studies have documented that latent heating associated with cumulus convection is the most significant energy source for the tropical disturbances (e.g., Lau and Lau 1992; Chen and Sui 2010). Tam and Li (2006) pointed out that enhanced convection associated with increased specific humidity at the top of the planetary boundary layer plays an important role in wave growth to the west of 150°E. Using a baroclinic model that incorporates convective heating, Li (2006) stated that the synoptic wave train is a result of the instability of the summer mean flow over the WNP with a convection–frictional convergence feedback.

In addition, off-equatorial TD-type disturbances transiting from equatorial MRG waves also exhibit a remarkable interannual variation. Based on reanalysis data, Chen and Huang (2009) documented that the longitudinal location of an equatorial to off-equatorial transition of wave perturbations has a good correspondence with the east–west shift of the monsoon trough during different oceanic thermal states. Furthermore, tropical cyclogenesis during years with a strong monsoon trough is more likely related to this transition than during years with a weak monsoon trough because of a more rapid growth of waves along a strong monsoon trough. However, the observational analysis fails to assess quantitatively key physical mechanisms controlling the interannual variation of synoptic wave transition, especially the relative roles of the dynamic and thermodynamic effects associated with monsoon circulation in modulating wave behaviors. Therefore, a thorough understanding of the extent to which the distinction in wave behaviors during different years can be ascribed to dynamic or thermodynamic effects requires a further examination by means of numerical approach. As an extension of work by Chen and Huang (2009), this study utilizes a simple baroclinic anomaly model to reproduce the marked differences in the wave characteristics during the wave transitions between the two types of ENSO events, and to investigate which mechanism is mainly responsible for these disparities. The paper is organized as follows. In section 2, the model and data are introduced. The model initialization and basic field are described in section 3. The numerical results in the control and dry runs are demonstrated in section 4 and 5, respectively. The roles of the near-surface thermodynamic effect and the related physical interpretation are presented in section 6. Finally, a summary and discussion are given in section 7.

2. Model setup and data

The global spectral baroclinic anomaly model used in this study is based on the dynamic core of the Geophysical Fluid Dynamics Laboratory AGCM (Held and Suarez 1994). The modified version has an equally distributed five-level sigma coordinate. It consists of primitive equations linearized by a realistic three-dimensional basic state but retains full nonlinearity in the second-order perturbation terms of the prediction equations so that the evolution of a specified initial perturbation can be examined (see the appendix for detailed description of the model). Using this model, Wang et al. (2003) studied an equatorially asymmetric atmospheric response to a symmetric forcing, and Li (2006) examined the origin of the synoptic wave in boreal summer over the WNP. The model has a horizontal resolution of T79. Rayleigh friction is set with a damping time scale of 2 days at the lowest model level (σ = 0.9) to mimic the planetary boundary layer dissipation and 10 days at other levels to represent the free atmosphere. Newtonian cooling with an e-folding time scale of 10 days is applied to all levels in the temperature equations.
To examine the impact of different basic fields on the wave transition, the two types of background states corresponding to strong ENSO events are obtained from monthly National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis (Kalnay et al. 1996). Based on a threshold of ±1.0°C from a 3-month running mean of the Extended Reconstruction Sea Surface Temperature (ERSST) anomalies in the Niño-3.4 region (5°N–5°S, 120°–170°W) during July–September (JAS), the summers of 1965, 1972, 1982, 1987, 1997, and 2002 and of 1964, 1973, 1975, 1988, 1998, and 1999 are chosen as El Niño (EN) and La Niña (LN) events, respectively. The realistic JAS-mean atmospheric fields for the two kinds of ENSO years are linearly interpolated to model sigma levels from original standard pressure levels.

To represent the role of convective heating related to circulation–convection feedback (CCF) in the wave behaviors, the convection process is simply parameterized in the model following Wang and Xie (1997), in which the perturbation convective heating is primarily determined by the near-surface thermodynamic factors associated with the low-level moisture and sea surface temperature (SST), and the dynamic factor associated with the vertical motion at the top of the planetary boundary layer (PBL). According to the Ekman PBL theory, the vertical motion is approximately proportional to the vorticity at the top of the PBL. Therefore, the convective heating parameterization is expressed as follows:

\[ Q' = \alpha \delta \frac{\zeta}{\xi} f(\sigma), \]

where \( \xi \) denotes the moisture within the PBL, which is designated as the seasonal-mean specific humidity at 2 m above the surface, and \( \zeta \) represents the perturbation vorticity at the top of the PBL. Heating coefficient \( \alpha \) denotes the strength of the CCF, which is prescribed as such that a PBL vorticity of \( 10^{-5} \) s\(^{-1}\) corresponds to a heating rate of 1°C day\(^{-1}\), approximately equivalent to 1.0 mm of precipitation per day, which is basically in agreement with the observed anomalous precipitation (e.g., Jin and Hoskins 1995; Annamalai and Sperber 2005). Also, \( \delta \) is a SST-dependent heating coefficient (Wang and Li 1993), such that \( \delta = 1 \) when SST \( > 29.5°C \), \( \delta = 0 \) when SST \( < 26.5°C \), and \( \delta = (\text{SST} - 26.5)/3 \) when \( 26.5°C < \text{SST} < 29.5°C \). Additionally, \( f(\sigma) \) represents the vertical profiles of the heating. For this study, the maximum heating is set in the middle troposphere at \( \sigma = 0.5 \), and is multiplied by weight coefficients of 0.2, 0.7, 0.5, and 0.1 at \( \sigma = 0.1, 0.3, 0.7, \) and 0.9, respectively, to represent the vertical variation of heating.

3. Model initialization and basic field

The transition from equatorial MRG waves to off-equatorial TD-type disturbances is a common phenomenon during boreal summer. To investigate the wave transition, the initial perturbation is designed as a MRG wave structure following the work of Matsumoto (1966). The horizontal wind profiles can be expressed from linear shallow water theory:

\[ u_0' = -\beta y v_0/(\omega - kc_0) \exp(-y^2/2L_0^2) \sin(kx), \]
\[ v_0' = v_0 \exp(-y^2/2L_0^2) \cos(kx), \]

where the perturbation velocity magnitude \( v_0 = 0.1 \) m s\(^{-1}\); the planetary vorticity gradient \( \beta = 2.3 \times 10^{-11} \text{m}^{-1} \text{s}^{-1} \); the wavelength \( L_0 = 6600 \) km; the wavenumber \( k = 2\pi/L_0 \); and the gravity wave speed \( c_0 = \sqrt{gh} \), in which the equivalent depth \( h = 200 \) m. The frequency \( \omega \) for an MRG wave is given by

\[ \omega = kc_0/2 - [(kc_0/2)^2 + u\beta c_0]^1/2. \]

An MRG wave with a symmetric meridional wind and an antisymmetric zonal wind about the equator is initialized for the model integration (Fig. 1), consistent with the shallow-water theoretical structure. The vertical structure of the MRG wave is simply set to a wavenumber-1 baroclinic structure in the equally distributed five sigma levels (i.e., the horizontal structures at \( \sigma \) = 0.1 and 0.3 are opposite phases, with counterparts at \( \sigma \) = 0.7 and 0.9).

The composite summer monsoon fields show remarkable differences between the two kinds of ENSO events, as displayed in the composite charts (Fig. 2). During EN years, warm SSTs greater than 29°C exhibit a zonally elongated feature with the warm water concentrating over the central Pacific. Correspondingly, the monsoon trough at 850 hPa extends southeastward close to the date line and anomalous westerlies prevail over the tropical western Pacific. The moist atmosphere covers a large fraction of the WNP as inferred from the distribution of specific humidity with a contour of 19 g kg\(^{-1}\) across the date line (Fig. 2a). In contrast, during LN years, the maximum SST is mainly distributed on the warm pool of the WNP with a large latitudinal extension from the equation to 20°N. As a response to SST anomaly over the WNP, the monsoon trough retreats northward, and the easterly flows dominate east of 130°E. Correspondingly, the region of large specific humidity is located to the west of 160°E (Fig. 2b). The major differences between two kinds of ENSO events are characterized by the strong westerly anomalies over the tropical WNP and the eastward-shifting warm SST and low-level moisture (Fig. 2c).
4. Simulated wave trains in ENSO events

a. Simulated wave characteristics

To compare the wave characteristics under the different background, the wave evolutions corresponding to the two types of ENSO events were examined in the model with realistic mean flows and surface parameters (hereafter referred to as CTL runs). Figure 3 shows the wave growth of the maximum eddy kinetic energy (EKE) at different sigma levels. Because of the presence of CCF, the amplitudes of wave trains during the two events appear to increase rapidly after a 2-day adjustment. Except at the top level, the eddy kinetic energy at the different levels experiences a comparable growth in the EN or LN runs. Since the heating profiles have relatively large magnitudes at the mid- to upper levels of $\sigma = 0.5$ and 0.3, the growth at these levels can be attributed to wave response to tropospheric convective heating. By comparison, although the heating strength is set to be relatively small at the lower levels, the favorable dynamic factors associated with the basic fields can provide an additional energy source for the growth of eddy kinetic energy, which will be discussed in the next subsection. On the other hand, the wave growth rate is much faster during EN events compared with that during LN events. At the sixth day of integration, the magnitude of perturbation during EN events is about twice as great as that during LN events. The fact that the waves experience a more rapid growth during EN events than during LN events is consistent with the conclusion of Chen and Huang (2009), who, however, only emphasized the dynamic role of the kinetic energy conversion from mean flow in the wave growth in the energy budget analysis.

In addition to the distinct growth rate of perturbations, the horizontal characteristics of the wave trains also exhibit remarkable differences in terms of the wave scale, the transition location, and the propagation direction as shown in Fig. 4. Although both of the wave trains experience a scale contraction during the wave transition in both types of ENSO years, the wave structure with a wavelength of 2000 km during EN years seems to be tighter than its counterpart with a wavelength of 2400 km during LN years, which can be attributed to the differences in the strength of zonal wind convergence and the wave growth rate in the presence of CCF. During EN years, as the zonally elongated monsoon trough penetrates eastward, the westerly flows to the south of monsoon trough meet the southeasterly trade winds, giving rise to a strong zonal wind convergence ($-\partial \bar{u}/\partial x > 0$). In contrast, during LN years, the monsoon trough retreats northwestward, yielding winds with a more northerly component and thus weakening the zonal wind convergence. Considering the zonal wavenumber change following a ray in a time-invariant mean flow—that is, $dk/dt = -k(\partial \bar{u}/\partial x)$—the opposing zonal flows of convergence zone can contract the zonal scales of westward-propagating waves (Webster and Chang 1988). Therefore, the strong zonal wind convergence tends to contract the wave scale more during EN years than during LN years. On the other hand, a more intense wave train embedded in a favorable environment is also more likely to contract its horizontal scale through a circulation–convection positive feedback, which will be discussed in section 6.

In addition, the wave transitions occur at different longitudes, which are represented by the location of the MRG wave deviation from the equator. During EN years, the equatorially trapped MRG waves move away from the equator, evolve into TD-type disturbances at about 165°E, and then propagate northwesternward. In contrast, the deflection of the MRG waves from the

![Figure 1](https://example.com/fig1.png)

**Fig. 1.** Initial perturbation of wind field (vectors), zonal wind (shaded), and meridional wind (contours) associated with a westward-propagating equatorial MRG wave.
equator occurs to the west of 160°E during LN years. This suggests that there is a pronounced east–west shift of wave transition during the two kinds of ENSO events. Another distinct feature to note is the difference in the propagation direction. Although the wave trains both are oriented northwest–southeast, the northward component in the wave train orientation is more remarkable during EN years while the zonal propagation is dominant during LN years. Moreover, the additional experiments (not shown) corresponding to the individual EN and LN year also indicate that the wave evolutions are qualitatively consistent with those corresponding to the composite ENSO years as shown in Fig. 4. Besides, in order to facilitate straightforward comparison, linear regressions in the reanalysis data are performed to exhibit the distinction of the observed wave trains during EN and LN years (Fig. 5). The wave structures in reanalysis data also show similar differences during the two kinds of ENSO events, which is basically consistent with the results in the model. It is noteworthy that the linear regression with the involvement of all daily samples reflects the climatology of synoptic wave train, while the simulated waves in the model experience a positive feedback process in the presence of CCF and thus more rapid scale contraction. Therefore, the wave scales in regression are found much broader than those in the model.

The wave propagations are demonstrated using the cross sections along their respective displacement directions.
The wave trains have a similar phase speed of about 11.5 m s\(^{-1}\) in the two types of years, which agrees reasonably with the observations (Liebmann and Hendon 1990; Takayabu and Nitta 1993). Considering the different propagation direction, the projected westward-propagating phase speed is much slower during EN years compared to that during LN years. The enhanced eastward-extending westerlies south of the monsoon trough during EN years not only reduce the wave scale, but also slow down the wave phase speed through a Doppler shift effect. Besides, the wave trains display a northwestward tilt with altitude, so the vertical structures look like a first baroclinic mode (Fig. 7). This feature is consistent with the structure of synoptic disturbances documented in previous studies (Reed and Recker 1971; Maloney and Dickinson 2003).

**b. Energetics of TD-type disturbances**

An analysis of the energy budget can improve understanding of the development of the TD-type disturbances in the model incorporating the CCF process. In this subsection, the energy conversions in terms of EKE and eddy available potential energy (EAPE) are estimated to distinguish the relative contribution of dynamic and thermodynamic processes to the wave growth.

The energy budget formulations used here follow those derived in Lau and Lau (1992) and Maloney and Dickinson (2003), which are expansions of the 2D barotropic kinetic energy budget used in Maloney and Hartmann (2001). Any variable \(a\) in this analysis is divided into two parts, the spatial-dependent JAS basic state and the simulated perturbation in the model, denoted by \(a_{\text{clim}}\) and \(a'\), respectively. In this analysis, \(\bar{a}\) denotes an average over one wave cycle. The EKE balance equation can be written as

\[
\frac{\partial K}{\partial t} = -\nabla_h \cdot (\nabla V_h) V_{h_{\text{clim}}} - \frac{R}{P} \omega T' - \nabla \cdot (\nabla' \Phi') - \nabla_{\text{clim}} \cdot \nabla K - \nabla' \cdot \nabla K + D,
\]

where \(K = (u'^2 + v'^2)/2\) is the horizontal EKE, and other symbols follow conventional definition. The first term on the right-hand side of Eq. (4) represents energy conversion from mean kinetic energy (MKE) to EKE. The second term stands for conversion from EAPE to EKE. These two terms are considered true sources or sinks of EKE. The other terms describe the redistribution of perturbation energy, which include the generation/destruction of EKE by local convergence of eddy geopotential flux (third term), the advection of EKE by the mean background flow and the transient fluctuations (fourth and fifth terms), and the dissipation of EKE by frictional effect (last term). Previous studies show that, in contrast to the first three terms, the other terms are negligibly small.

The EAPE energy balance equation can be expressed as

\[
\frac{\partial A}{\partial t} = -\nabla_h \cdot (\nabla V_h T_{\text{clim}}) + \frac{R T'^{\omega}}{P} + \frac{R}{C_p S_p P} Q T',
\]

(Fig. 6).
where $A = RT^2/2SP_P$ is EAPE, $S_p = -T_{\text{clim}}(\partial \ln \theta_{\text{clim}}/\partial p) = RT_{\text{clim}}/C_p P - \partial T_{\text{clim}}/\partial p$ the static stability, $R$ the gas constant, $C_p$ the specific heat at constant pressure, and $Q'$ the convective heating in the CCF process. On the right-hand side of Eq. (5), the first term represents baroclinic conversion from mean available potential energy (MAPE) to EAPE, the second term is opposite to the KP term in the Eq. (4), and the third term denotes the diabatic heating effect.

Figures 8 and 9 show the four major terms representing the barotropic conversion from MKE to EKE, the conversion from EAPE to EKE, the baroclinic conversion from MAPE to EAPE, and EAPE generation by diabatic heating in the EN and LN runs. Comparing Figs. 8 and 9, the regions of positive energy conversion in the EN and LN runs also appear spatially different. The energy sources contributing to the EKE and EAPE in the EN run are primarily located to the east of $140^\circ$E while the energy conversions peak around the Philippines in LN years, which is coincident with the region of wave activity shown in Fig. 4. Besides, the magnitudes of energy conversions in the four terms during EN years are much larger than their counterparts during LN years, consistent with distinct perturbation growth rates. In the EN run, the comparatively favorable dynamic environment induces synoptic wave growth at the initial stage, and then the perturbation amplitude can be magnified through the circulation–convection positive feedback process, producing a more rapid wave growth than is the case in LN years. However, it should be noted that the energy conversions in both runs appear much larger than the observed. For example, the barotropic conversion in the model is more than twice as much as the observational diagnosis in previous studies (Lau and Lau 1992; Chen and Huang 2009), which can be closely linked to the rapid wave development in the run involving CCF process.

Regarding the individual conversion term, both of the runs show that the areas of major EKE and EAPE conversion are basically aligned along the orientation of synoptic wave development. For the southwest–northeast phase-tilted perturbation, the barotropic conversion from...
MKE to EKE primarily depends on the pattern of mean flow associated with the monsoon trough. The cyclonic shear and convergence along the trough axis can generate the positive barotropic conversion (Figs. 8a, 9a). In contrast, the conversion of EAPE to EKE through the rising (sinking) motion of warm (cold) air provides more appreciable energy sources for the EKE growth than the barotropic conversion process (Figs. 8b, 9b). However, since $\nabla \cdot (V'\Phi') = -\nabla \cdot V'\Phi' - \Phi' (V \cdot V') = -\nabla_h \cdot V_h \Phi' + (R/P) \omega^2 T'$, in which the term $(R/P)\omega^2 T'$ is dominant, the conversion of EAPE to EKE is almost offset by local convergence of the eddy geopotential flux in the third term on the right-hand side of Eq. (4). Therefore, as a generation source of EKE, the barotropic conversion plays an important role in the EKE growth.

The energy conversion from EAPE to EKE in Eq. (5) destroys EAPE, which can be compensated by the baroclinic conversion from MAPE to EAPE and diabatic heating. By comparison, the baroclinic conversion, depending on the environmental meridional temperature gradient and eddy heat flux, makes a comparatively small contribution to the generation of EAPE, owing to weak temperature gradient in the tropics (Figs. 8c, 9c). The perturbation diabatic heating, the most dominant energy source, can partly balance the loss of the EAPE–EKE conversion (Figs. 8d, 9d) and generate the EAPE in combination with the baroclinic conversion. It is evident

FIG. 6. The temporal evolution of the normalized meridional wind along the cross sections (see line segments in Fig. 4) for (a) El Niño and (b) La Niña years at 850 hPa from day 3 to day 5. The contour interval is 0.3.

FIG. 7. Vertical structures of the normalized meridional wind along the cross sections (see line segments in Fig. 4) for (a) El Niño and (b) La Niña years. The contour interval is 0.2.
that the axis of maximum diabatic heating is coincident with the axis of perturbation growth in the tropics, implying that the diabatic heating acts as a crucial energy source for the development of synoptic waves over the WNP. The above results also support the argument in previous studies that the convective heating acts as a leading energy source to supply the wave growth and that the increase in EKE is directly linked to barotropic conversion in the monsoon region over the WNP, although the magnitudes of energy conversions appear to be much greater than those in the observations because of a rapid perturbation growth with the involvement of CCF process in the dynamic framework linearized by a realistic three-dimensional basic state.

5. Impact of dynamic factors

The last section illustrates different wave characteristics corresponding to the distinct environmental conditions in the two kinds of ENSO events. The role of the background environmental field involves the dynamic effect of three-dimensional mean flows and the near-surface thermodynamic effect associated with convective heating determined by surface moisture and SST. It is desirable to understand their respective contributions to the wave features. For this purpose, this section examines the sensitive runs (hereafter referred to as DRY runs) in which the convective heating is switched off so that CCF process is no longer present.

As expected, switching off the convective heating cut off the primary energy source and in turn the CCF process. As a result, the maximum kinetic energy experienced a gradual decay due to the friction damping (not shown), suggesting that the summer mean flow alone cannot lead to the rapid perturbation growth in the tropics in the absence of the energy source from convective heating feedback. The result agrees with the least damped mode documented by Li (2006). However, Li (2006) further stated that the dynamic effect from the climatological summer flow does play a role in determining the preferred length scale, wave train structure, and propagation characteristics. The following
section will show that the near-surface thermodynamic effect can exert a decisive influence on most of the wave characteristics.

As shown in Fig. 10, the wave trains display a slow transition, considerably different from the results in the CTL runs. On the one hand, although the wave trains experience a scale contraction while migrating to the regions in which the basic flows are convergent, the spatial scales are much more expansive compared with those in the CTL runs. On the other hand, the MRG waves deflect from the equator and evolve into TD-like disturbances in such a way that the wave transition seems to be obscure. The northwestward-shifting wave trains have a more zonal component and a less meridional component in contrast to the evident northward displacement of the wave trains in the CTL runs as shown in Fig. 4.

In addition to the dynamic effect related to the convergence of zonal winds, the vertical wind shear can also contribute to determining the level of wave amplification and shifting the wave train northward. On the one hand, in the westerly vertical shear, the baroclinic and barotropic modes are nearly in phase, whereas they are 180° out of phase in the easterly vertical shear. Therefore, an easterly (westerly) vertical shear leads to the amplification of the waves at the lower (upper) level (Wang and Xie 1996). Because of the prevalence of the easterly vertical shear over the regions of wave transition during EN and LN years (Fig. 4), remarkable wave trains appear at the lower-tropospheric level.

On the other hand, using a 2.5-layer model, Jiang et al. (2004) derived a barotropic vorticity tendency equation in which the vertical wind shear can couple barotropic and baroclinic structures [see their Eq. (3)]. Specifically, consider a case of purely baroclinic structure at the initial time: the generation of the barotropic mode in the free atmosphere can be realized through the vertical shear of the mean flow acting on the meridional gradient of the baroclinic divergence. That can be expressed as follows:

$$\frac{\partial \zeta}{\partial t} \propto \pi \frac{\partial D}{\partial y}.$$  \hspace{1cm} (6)

Variables with a plus (minus) subscript represent a barotropic (baroclinic) mode. For a baroclinic structure with a convergence (divergence) in the lower (upper) troposphere, a maximum positive baroclinic

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**Fig. 9.** As in Fig. 8, but for the LN run. The value range and contour interval (10^{-5} \text{m}^2 \text{s}^{-3}) are also shown in the lower right corner of each plot.
divergence $D_-$ is located above a low-pressure vortex, with $\partial D_-/\partial y < 0$ ($\partial D_-/\partial y > 0$) existing to the north (south) of it. As a result, a positive (negative) barotropic mode of vorticity can be induced to the north (south) of a cyclonic vortex in the presence of the easterly vertical shear of the mean flow ($\pi_f < 0$). The difference in the distribution of vertical shear of zonal winds is illustrated in Fig. 4. The eastward displacement of tropical westerly flow during EN years enhances the easterly vertical shear over the eastern part of the WNP. By comparison, the easterly vertical shear during LN years is confined to the west of 150°E and has a relatively small magnitude. Consequently, the northward shift of the wave train during EN years occurs at a more eastern longitude than that during LN years. Moreover, the northward displacement of the wave train becomes more evident during EN years because of the vigorous easterly vertical shear acting on the baroclinic mode. However, it should be noted that the propagation of the wave trains fails to produce a reasonable northward component in the absence of convection heating in the two kinds of ENSO events. This also motivates us to discuss the role of near-surface thermodynamic effect in the next section.

6. Role of thermodynamic factors

The differences between the CTL and DRY runs are ascribed to the CCF process associated with near-surface thermodynamic factors, so the results in the CTL and DRY runs are compared in an attempt to unveil fundamental near-surface thermodynamic influence. In collaboration with the dynamical effect, the near-surface thermodynamic effect not only accelerates the scale contraction of wave train, but also affects the propagation characteristics.

Analogous to the TC formation, the mechanisms associated with the conditional instability of the second kind (CISK; Charney and Eliassen 1964) or wind-induced surface heat exchange (WISHE; Emanuel 1994) can trigger tropical cyclogenesis by a positive feedback process from a synoptic scale to a meso-$\alpha$ or even smaller scale. The rapid growth of wave in the presence of the convective heating feedback can deepen perturbation pressure in the core region of a cyclonic circulation, leading to an inward contraction of the circulation to balance the increased pressure gradient. Hence, the near-surface thermodynamic effect of convective heating can exert a more efficient and significant influence on the scale contraction of wave train than the dynamic effect related to the convergence of zonal wind in the tropical region.

In this model, the near-surface thermodynamic effect is represented by the perturbation convective heating $Q'$, which greatly depends on the heating coefficient associated with SST, mean moisture, and perturbation vorticity at the top of PBL ($Q' = \delta T_{KE}$. As mentioned in the last section, the baroclinic mode of divergence can initiate a positive (negative) barotropic vorticity to the north (south) of a low-pressure vortex in the presence of the easterly vertical shear of zonal winds. As a result, the generated cyclonic (anticyclonic) vorticity at the top of PBL can strengthen flow convergence (divergence) through the Ekman-pumping effect due to surface friction, which further leads to the enhanced (suppressed) convective heating to the north (south) of a cyclonic vortex. Figure 11 demonstrates the phase relationship between the convective heating and the low-level perturbed geopotential height. During either EN or LN years, the convective heating (cooling) leads the low
(high) pressure center by approximately one-quarter of a wavelength downstream of propagation. This phase discrepancy tends to yield one new cyclonic (anticyclonic) circulation center developing to the northwest of the baroclinic convergence (divergence), resulting in the northwestward displacement of the wave train.

Another question arises as to why the wave trains have a more northward propagation component in the CTL runs than in the DRY runs during EN and LN years; moreover, the wave train in EN years exhibits a more northward migration compared with the case in LN years. To address this question, the normalized near-surface thermodynamic coefficients $d\theta_E$ depending on SST and low-level moisture are depicted in Fig. 12. Distinct patterns of heating coefficients can be observed in Fig. 12. Accompanied by the eastward shift of SST and specific humidity for EN years, the large heating coefficient, originating from east of the date line, is oriented southeast–northwest (Fig. 12a). In contrast, the high value of heating coefficient in LN years is concentrated in the warm pool region east of the Philippines between 120° and 160°E, and is more zonally oriented (Fig. 12b).

To further verify the crucial modulation of near-surface thermodynamic factors on the wave propagation, two extra experiments are conducted in which the same climatological-mean dynamic background field (i.e., wind, temperature, geopotential height, and surface pressure) is prescribed, while the different thermal background fields associated with the CCF process (i.e., SST and low-level specific humidity) corresponding to EN and LN years are introduced. By comparison with the results in the CTL runs, the importance of near-surface thermodynamic process associated with CCF in modulating the wave behaviors can be indicated. As shown in Fig. 13, even although the extra runs are imposed by the same dynamic background field, the characteristics of the TD-type disturbances still exhibit remarkable differences between the two types of ENSO events due to the distinct thermal background fields. Corresponding to EN or LN years, the extra run can produce similar wave characteristics to those in the CTL run shown in Fig. 4. However, through

**FIG. 11.** The horizontal patterns of normalized heating rate (shaded) and perturbed geopotential height at day 4 (contours) for (a) El Niño and (b) La Niña years at 850 hPa. The shading and contour intervals are 0.2.

**FIG. 12.** The distributions of normalized thermal coefficient for (a) El Niño and (b) La Niña years. The contour interval is 0.1. The contour of 0.9 is thick.

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a careful comparison near the equator between the extra runs and the CTL runs, the differences in the longitude of equatorial MRG wave transition can be detected. Specifically, in contrast to the results in the CTL runs, the location of wave transition in the extra run (Fig. 13a) seems to shift westward by about \( \frac{5}{8} \) of longitude during EN years, while the eastward shift from 155°E to 160°E in the extra run (Fig. 13b) can be observed during LN years. As a result, the wave transitions in the two extra runs exhibit an identical longitudinal location. These modifications in wave transition location between the extra runs and the CTL runs should be attributed to the involvement of the same dynamic background field in the model. In sum, the dynamic field decides primarily the location of wave transition at the initial stage, whereas the thermal field plays a crucial role in contracting the wave scale and modulating the wave propagation direction. Once the northward shift of wave train is initiated in the presence of easterly vertical shear, the near-surface thermodynamic coefficients begin to take effect by acting on the convective heating term, and then steer the wave train toward the more warm and moist ocean by a CCF process. Hence, in collaboration with the dynamic effect, the near-surface thermodynamic effect exerts an essential influence on the propagation of wave train.

7. Conclusions and discussion

The differences in wave characteristics during the transition from an MRG wave to a TD-type disturbance between two types of ENSO events are investigated using a global baroclinic anomaly model in which the corresponding realistic 3D summer mean basic states are specified. Using the numerical approach, this study aims to reproduce reasonably the major differences in the wave transition between two types of ENSO events given the distinct dynamic and near-surface thermodynamic environmental backgrounds, and assess the relative roles of the dynamic and near-surface thermodynamic effects related to SST and low-level moisture in the wave transition.

The equatorially trapped MRG waves initialized in the CTL runs are embedded within the different summer mean fields corresponding to EN and LN years. During EN years, following the eastward shift of warm SST, the high moisture dominates over the eastern part of the WNP and the westerly winds penetrate toward the date line along with the eastward-extending monsoon trough. These conditions provide a favorable atmospheric environment for wave development and transition to the east of 160°E. In contrast, during LN years, the warm and moist region retreats westward and the monsoon trough becomes weakened, leading to the westerly flows located over the Philippines. These discrepancies in the background fields are responsible for a more unstable mode in the presence of CCF and a more eastern longitude of wave transition during EN years compared with during LN years. In addition, although the wave trains bear some similarities in terms of the phase speed and vertically tilted structure along the orientation of wave trains, there exist markedly distinct projections in the zonal and meridional directions due to different northward components of wave propagation during the two kinds of ENSO years. The energetic analysis reveals that the diabatic heating associated with CCF and baroclinic conversion jointly convert energy to EAPE, which is further supplied to EKE through the negative correlation of perturbation temperature and pressure vertical

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**FIG. 13.** The horizontal patterns of normalized meridional wind at day 4.5 in the extra runs for (a) El Niño and (b) La Niña years at 850 hPa. For comparison, the normalized meridional winds in the CTL runs shown in Fig. 4 are shaded. The shading and contour intervals are 0.2.
velocity. The EKE produced by the conversion from EAPE and barotropic conversion can be partly redistributed by the convergence of eddy geopotential flux and advection by mean and perturbation wind.

The dynamic effect is examined in the DRY runs with the removal of convective heating. The pure dynamic effect not only produces the decaying modes due to the friction, but also partly modulates the wave behaviors. However, the dynamic effect alone fails to yield a satisfactory wave scale contraction and a northward-shifting component. This suggests that the near-surface thermodynamic effect is important for the wave nature during the wave transition. The differences in the wave features between the CTL and DRY runs imply the contribution from the near-surface thermodynamic effect. Of prominence is that the scale contraction is accelerated as the waves intensify, and a more northward-propagating component appears. The shrinking of the wave scale is readily detected in an intensified vortex system due to an approximate balance of dynamics. A reasonable propagation direction can be achieved through the near-surface thermodynamic effect. Initially, a northward shift of wave train is triggered by a baroclinic mode with differential convergences at lower and upper levels, which acts to give rise to a positive tendency of barotropic vorticity to the north of a cyclonic vortex in the regions of easterly vertical shear. Then, the near-surface thermodynamic factor combining the actions of SST and low-level moisture can act on the convective heating in a simple parameterization scheme. Consequently, the orientation of convective heating is significantly determined by the spatial pattern of the near-surface thermodynamic field. It is the distinction in the mean-summer near-surface thermodynamic state to make the differences in the wave propagation during the two kinds of ENSO events.

In this study, with the aid of the numerical experiments, the relative roles of dynamic and near-surface thermodynamic effects in modulating the synoptic wave train during the transition from MRG waves to TD-type disturbances are examined. Keep in mind that in the current theoretical baroclinic anomaly model, the background dynamic and near-surface thermodynamic fields from the climatological mean are fixed so that the wave–flow interaction and the modulation of synoptic waves in moisture field are ignored. Moreover, a simple heating scheme considering the CCF process is employed and an idealized vertical profile of heating is specified because of the coarse vertical resolution in this model, which can give rise to the crude wave structures. Nevertheless, the reasonable reproduction of the wave behaviors during EN and LN years in this simplified baroclinic model gives us credible results to help understand the underlying mechanisms in which the wave behaviors differ under the different background states.

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**APPENDIX**

**A Baroclinic Anomaly Model Framework**

The momentum, temperature, and continuity equations of the multilevel baroclinic model in a vertical sigma coordinate can be expressed as

\[
\frac{\partial \mathbf{v}}{\partial t} = -\nabla \phi - RT_0 \nabla \rho S + N_M, \\
\frac{\partial T}{\partial t} = \frac{\kappa T_0}{\sigma} T_D - \kappa T_0 (D) + N_T, \quad \text{and} \\
\frac{\partial \ln \rho S}{\partial t} = -\langle D \rangle + N_C,
\]

where \(T_0 = 250 \text{ K}\) is a reference atmospheric temperature, \(\sigma = \sigma_D + \sigma_A\) represents vertical velocity in the sigma \((\sigma = P/P_S)\) coordinate, \(\sigma_D = \int_0^\sigma (D - \langle D \rangle) \, \text{d}\sigma, \sigma_A = \int_0^\sigma (V - \langle V \rangle) \cdot \nabla \ln \rho S \, \text{d}\sigma,\) and angle brackets denote a vertical average from surface to the top of atmosphere. Here \(N_M, N_T,\) and \(N_C\) are nonlinear terms that would be calculated in a spectrum space, having the following forms:

\[
N_M = -(\xi + f) \mathbf{k} \times \mathbf{v} - \frac{\partial \mathbf{v}}{\partial \sigma} \cdot \mathbf{V} E - R(T - T_0) \nabla \ln \rho S,
\]

\[
N_T = Q - \mathbf{V} \cdot \nabla T - \frac{\partial \mathbf{v}}{\partial \sigma} \cdot \mathbf{V} \cdot \mathbf{V} + \kappa(T - T_0)(D) + \mathbf{V} \cdot \nabla \ln \rho S
\]

\[
+ \frac{\kappa(T - T_0)}{\sigma} F + \frac{\kappa T_0}{\sigma} F A, \quad \text{and} \\
N_C = -\langle V \rangle \cdot \nabla \ln \rho S.
\]

The basic-state field can approximately satisfy the governing equations, which implies that the effect of atmospheric perturbations on the climatologically mean basic state is negligible in the tropics. Therefore, the perturbation governing equations can be derived by subtracting the basic-state equations from the total equations:

\[
\frac{\partial \mathbf{v}'}{\partial t} = -\nabla \phi' - RT_0 \nabla \rho S' + N_M'. \tag{A1}
\]
\[ \frac{\partial T'}{\partial t} = \frac{\kappa T_0}{\sigma} \delta_D' - \kappa T'_0 \langle D' \rangle + N'_T, \quad \text{(A2)} \]

\[ \frac{\partial \ln P'_C}{\partial t} = -\langle D' \rangle + N'_C, \quad \text{(A3)} \]

where \( N'_i = N_i(\bar{a} + a') - N_i(\bar{a}) \); the subscript \( i \) corresponds to the \( M, T, \) and \( C \) for different equations; \( a \) represents model-dependent variables; a prime represents a perturbation field; and an overbar denotes the basic state field. This global anomaly model comprising perturbation equations (A1)–(A3) can be used to examine the evolution of initial perturbations affected by the basic-state fields. A realistic summer mean state of \( \bar{u}, \bar{v}, \bar{T}' \), and \( \bar{P}'_s \) is prescribed as the basic state. The summer-average near-surface thermodynamic factors related to sea surface temperature and specific humidity are also input to calculate the heating in the nonlinear term \( N'_T \) by a simplified parameterization scheme. Also, the initial condition corresponding to equatorial MRG structure in the present study is designated for the model integration.

REFERENCES


